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Tiltmeter Instrumentation for Deep Hole Operation

Arthur D. Little, Inc.

prepared for

Air Force Office of Scientific Research

FEBRUARY 1973

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TILTMETER INSTRUMENTATION FOR DEEP HOLE OPERATION FINAL TECHNICAL REPORT

prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
ARLINGTON, VIRGINIA

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ARPA ORDER NO. 1584

AMENDMENT NO. 5

14 FEBRUARY 1973

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FINAL TECHNICAL REPORT

15 June 1972 through 14 December 1972

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13. ABSTRACT

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One of the systems is installed at a depth of 1860 ft. in a borehole drilled into the granitic rock typical of the Gabilan Range formation; the borehole is cased down to 1900 ft. and cemented to the formation. The other system is installed in a shallow borehole (40 ft.) drilled into the overburden, within 100 ft. of the deep borehole.

Preliminary data indicate that the site is highly active, both seismically and tectonically. Movements of the tilt vector, as reconstructed from recordings of the two components of tilt, are large in magnitude (tens of μrad.) and frequent in occurrence.

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Deep hole instrumentation						
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Earth strain and tilt measurement						
Tectonic tilt						
Fault movement monitoring						
Earthquake prediction						
Uplift from fluid injection or removal						
Oil-well instrumentation						

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I. SUMMARY

This final report describes in detail two deep hole tiltmeter systems and their installation at Stone Canyon in Central California. The principal characteristics of the systems are: tilt range, in excess of ± 300 μrad.; tilt resolution, better than 0.1 μrad.; maximum ambient operating pressure, 5000 psi; maximum ambient operating temperature, 75°C; minimum size of borehole, 6 in. I.D.; cables supplied, seven conductors, double S.S. armor, 5300 and 2300 ft.

One of the systems is installed at a depth of 1860 ft. in a borehole drilled into the granitic rock typical of the Gabilan Range formation; the borehole is cased down to 1900 ft. and cemented to the formation. The other system is installed in a shallow borehole (40 ft.) drilled into the overburden, within 100 ft. of the deep borehole.

Preliminary data indicate that the site is highly active, both seismically and tectonically. Movements of the tilt vector, as reconstructed from recordings of the two components of tilt, are large in magnitude (tens of μrad.) and frequent in occurrence.

II. DEEP HOLE TILTMETER SYSTEMS DBT-1 AND DBT-2

A. INTRODUCTION

Development of the deep hole tiltmeter systems has been described at length in our previous reports of June 14, 1971, December 15, 1971 and July 15, 1972. These reports should be consulted for the background and development details not covered in this report.

The principal operating parameters and dimensions of the two systems as completed are given in Table I. The following text presents additional information necessary for understanding the peculiarities of the systems and for their proper operation, removal and reinstallation. However, this report is not intended to be a service and repair manual. Most of the equipment described herein is of a prototype nature, and some of it is in used condition, since it has been operated over extended periods of time in the laboratory and afield.

If malfunctioning occurs and/or repairs seem to be necessary, it is recommended that the personnel of Arthur D. Little, Inc., be contacted (see list of authors in the attached Form DD 1473).

Two systems, henceforth designated as DBT-1 and DBT-2, have been built and installed. Each system consists of three units: the downhole instrument package, the uphole control electronics, and the instrument cable. In addition to these essential components, various accessories, spares and tools are provided and will be described below.

B. DOWNHOLE INSTRUMENT PACKAGE

The downhole package resembles an oil-well logging tool, since it was, in fact, designed for use in oil wells. It consists of four parts: the holelock, the tiltmeter, the electronics, and the cable coupling, as shown in Figure 1. Detailed drawings of the downhole package are reproduced in our Report of June 14, 1970 (Figures 3, 4 and 5). A complete set of blueprints is furnished with the equipment.

1. The Holelock

The purpose of the holelock is to provide a firm base for the tiltmeter in the casing of the borehole. When locked at the selected depth, the holelock makes a four-point contact with the casing by its cam and the three "buttons" located opposite to the cam on the shoulders of the holelock body. The holelock was made by Teledyne-Geotech Co. of Garland, Texas, and cams of nominal sizes 3, 5 and 7 in. were obtained from the manufacturer. Several sets of buttons were fabricated to span a range of casing sizes from 5 3/4 in. to 11 in. I.D.

TABLE I

PHYSICAL CHARACTERISTICS OF THE DEEP HOLE TILTMETER SYSTEMS

Parameter	DBT-1	DBT-2
Tilt Range (min.)	± 200 μrad.	± 300 μrad.
Leveling Range (max.)	± 7°	± 7°
Tilt Resolution (min.)	.08 μrad.	.04 μrad.
Tilt Stability (zero drift)	< 1 μrad./mo.	(not determined)
Natural Period (approx.)	1 sec.	1 sec.
Damping (approx.)	0.4	0.4
Output Voltage (analog)	± 10 v	± 10 v
Data Transmission	analog, sequential scan, 8 channels	
Data Acquisition	digital printout, all channels (manual or automatic), plus external tape punch	
	or one channel continual (analog)	and one channel continual (analog)
Downhole Cable	2300 ft.	5300 ft.
(Vector Co. Type 7-46 NT)	7 conductors, 20 AWG and double armor, 316 stainless	
Downhole Package	5.25 in. O.D. 102 in. long	5.25 in. O.D. 102 in. long
Weight (in air)	306 lbs.	306 lbs.
Material of Case	Monel K-500	stainless 22-13-5
Operating Pressure (max.)	5000 psi	5000 psi
Operating Temperature (max.)	60°C	75°C
Holelock	Teledyne-Geotech Mod. 24080 (modified)	
Usable Well Casing Dia.	5 3/4 in. to 11 in. I.D.	

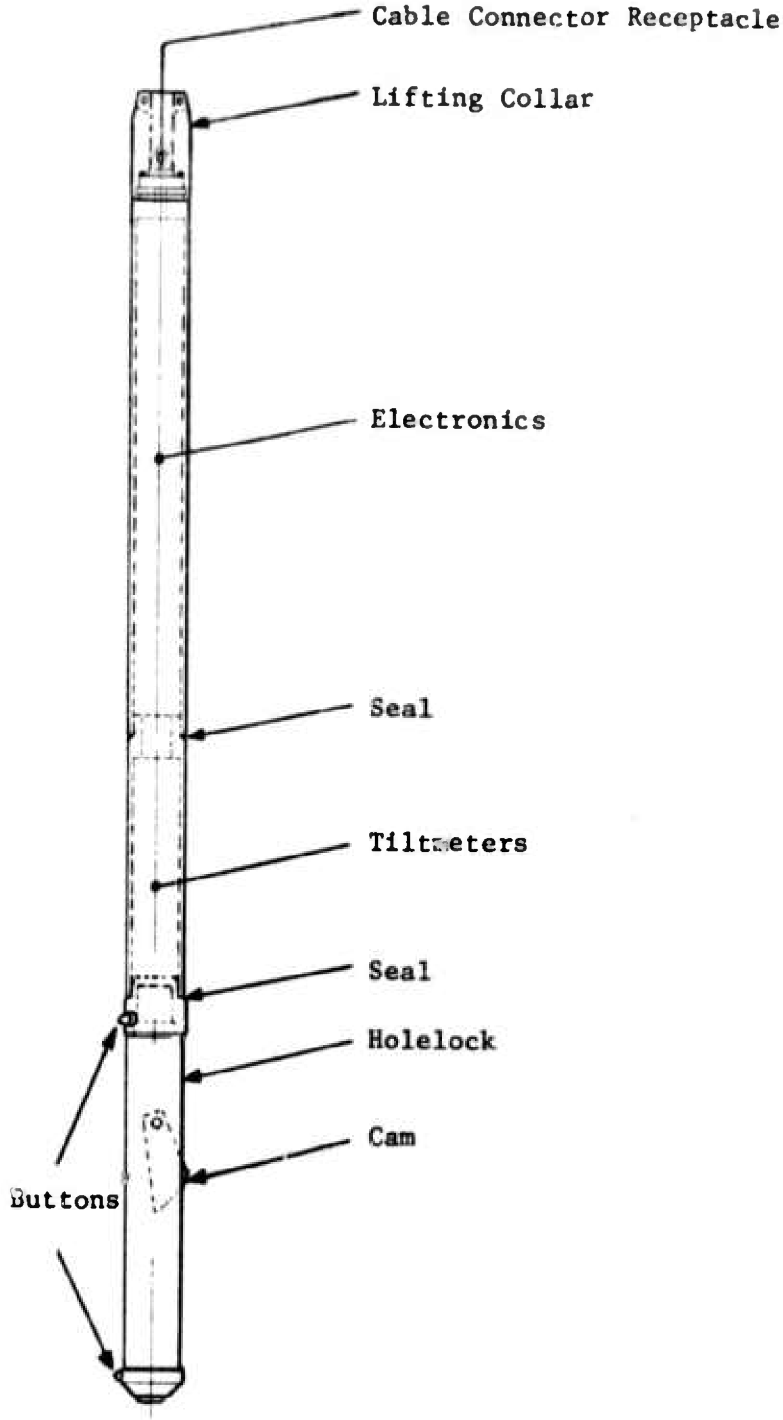

FIGURE 1

Downhole Package -- Identification of Parts

The cam of the holelock can be remotely operated by a built-in electric motor (45 v, 0.13 a, d.c.). When the downhole package reaches the predetermined depth in the borehole, the cam is operated (it takes 14 min. for its full extension), and the cable is slackened a few feet. The cam then jams firmly into the casing and holds the downhole package by its weight. The holelock cannot release itself until the cable is pulled up and the cam retracted.

For corrosion resistance during the extended period of operation in the well, the holelock is made of type 316 stainless steel, except for the cam which is made of a type 17-4, precipitation hardened steel. The buttons are made of type 22-13-5 alloy steel chosen for its high strength and corrosion resistance.

The top of the holelock serves as a base for the internal tiltmeter assembly to assure direct transfer of the tilt from the borehole casing to the tiltmeters. The top of the holelock is threaded (4 1/4 - 12 t.p.i.) and provided with a groove for the sealing ring of the pressure case containing the tiltmeters. In the center of the holelock top is a pressure-tight bulkhead connector (Vector No. MS(2)F-4/#16-BCR-P4) for the two wires of the holelock motor.

In addition to the two holelocks supplied with the DBT-1 and DBT-2, a third holelock is available as a spare. This unit was used for the initial tests, and it is not provided with tapped holes for the buttons. The body of this unit is made of nickel-plated tool steel.

2. Tiltmeters

The tiltmeters with their gimbals, remote leveling motors, preamplifiers and relays are mounted in a rigid tubular module. Three modules have been built of which Nos. 2 and 3 are incorporated in the DBT-1 and DBT-2 downhole units; No. 1 is a spare.

The tiltmeter module is bolted to the top of the holelock and otherwise is in no contact with the external pressure case which protects it from the well fluid. The case is made of a corrosion resistant metal of high yield strength (Monel K-500 in DBT-1 and type 22-13-5 alloy steel in DBT-2). It fits freely over the tiltmeter module and is screwed down over the threaded part of the holelock top. The face seal between the holelock and the case is made with a Teflon ring precisely machined to fill the matching grooves in the two parts. The groove dimensions are such that the seal zone must be chilled with dry ice during assembly to cause shrinkage of the Teflon ring. This shrinkage is necessary for the screw connection to be tightened without a gap. After warming up, the ring expands and fills the groove completely and becomes compressed in it.

The two tiltmeters are mounted in the module by means of a gimbal arrangement so that they can be leveled by remotely actuated motors about two orthogonal axes. The pivots for the gimbal ring rest in V-grooves

machined in the outer body of the module and are held down in them by a pair of springs. This arrangement eliminates all play in the pivot bearings, but it provides only a marginal support in the vertical direction.

For this reason it is important that the tiltmeter module and the assembled downhole package be never turned upside down. It is perfectly possible to handle the package in the horizontal position; however, it is recommended to do so with care, avoiding hard impacts. If the assembled downhole package is to be shipped by truck, it is recommended that it be propped up at an angle of approximately 45° upwards, and that it be padded and securely lashed down.

The direction of the + X-axis of the tiltmeter module is marked by a center punch on the outside of the holelock case. The + Y-axis is 90° clockwise from the + X-axis. After assembly of the complete downhole package, this orientation was transferred to its top and put in reference with the fiducial mark on the lifting collar as shown in Figures 2 and 3. Positive directions of the axes are defined as follows: + X-axis is that which upon rotation about Y-axis in CCW direction produces positive output voltage of the X-tiltmeter. Positive Y-axis is defined in the same manner.

Orientation of the axes should always be checked before placing the downhole package in the borehole. While the package is standing upright on the ground, it is tilted back and forth about its axes and the polarity of the output voltage is observed on the DVM of the control electronics panel.

3. Downhole Electronics

The downhole electronics module contains the ac/dc power supplies, the data multiplexer, the control function multiplexer and thermistor amplifiers. Block diagram of the downhole electronics is shown in Figure 4, which matches with the corresponding block diagram of the surface electronics shown in Figure 7. The electronics is fabricated in circuit boards which are fastened to a rigid aluminum frame whose circular base is bolted to the top of the tiltmeter pressure case. The electronics pressure case fits over it and is screwed down over the threaded part of the tiltmeter case top (4 1/2 - 12 t.p.i.). A Teflon ring fitting into a matching groove completes the face seal.

The connection with the uphole electronics requires seven conductors. A seven-pin receptacle is provided in the lowest part of the electronics module for a matching connector bringing down a seven-wire bundle from the bulkhead cable receptacle bolted to the top of the pressure case.

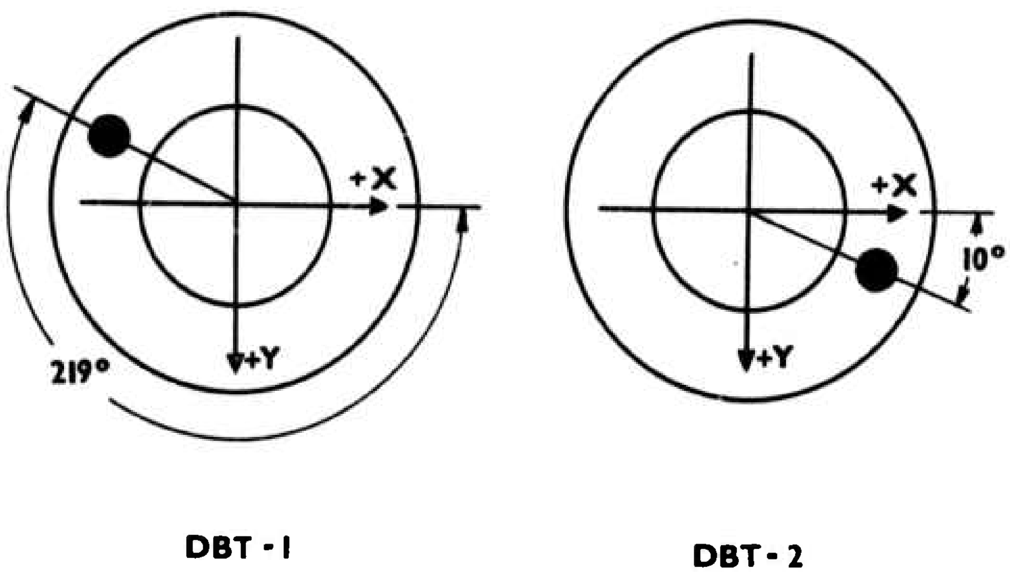

FIGURE 2

Orientation of Tiltmeter Axes, Viewed from the Top

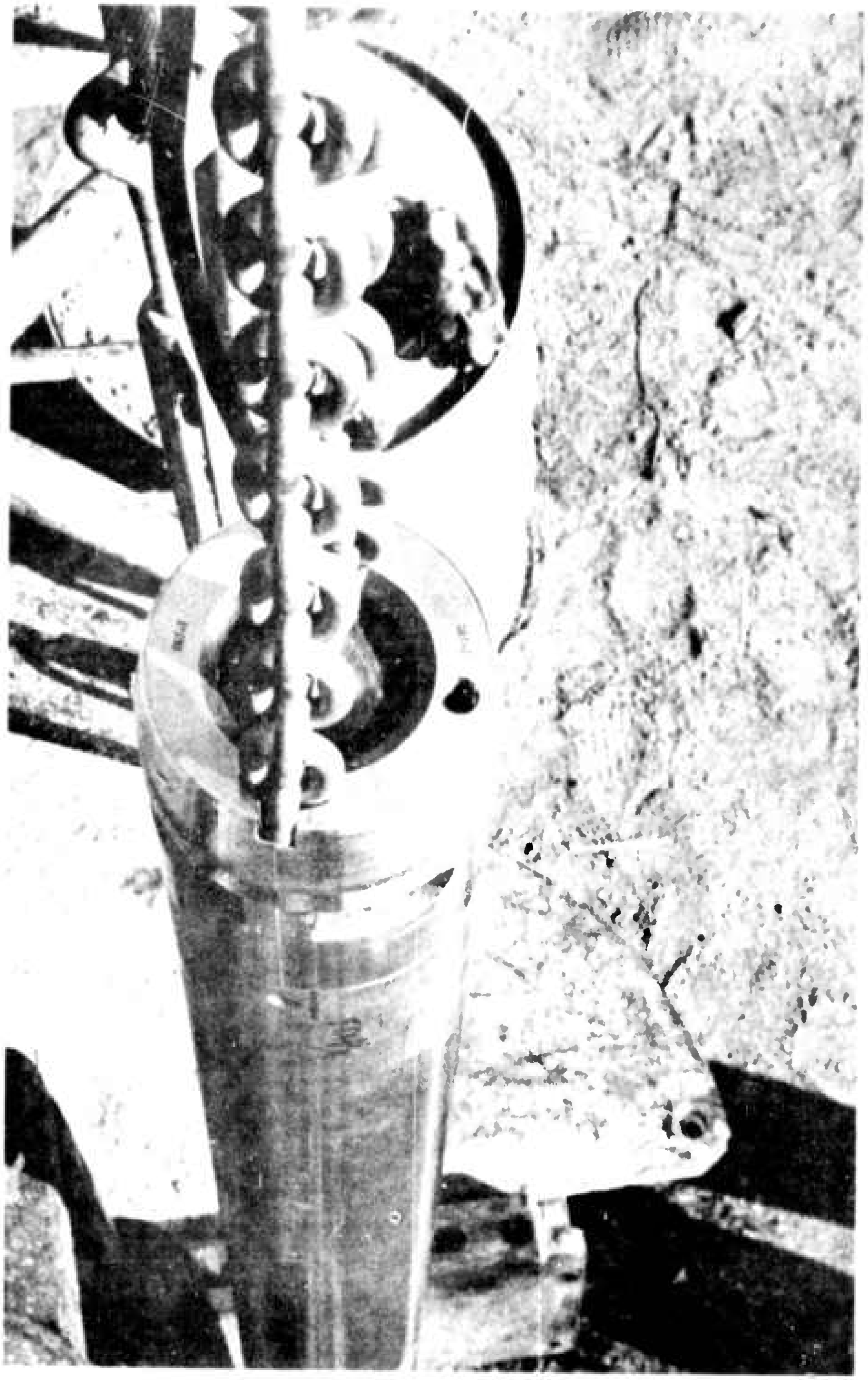

FIGURE 3

Lifting Collar with Decoupling Chains Attached

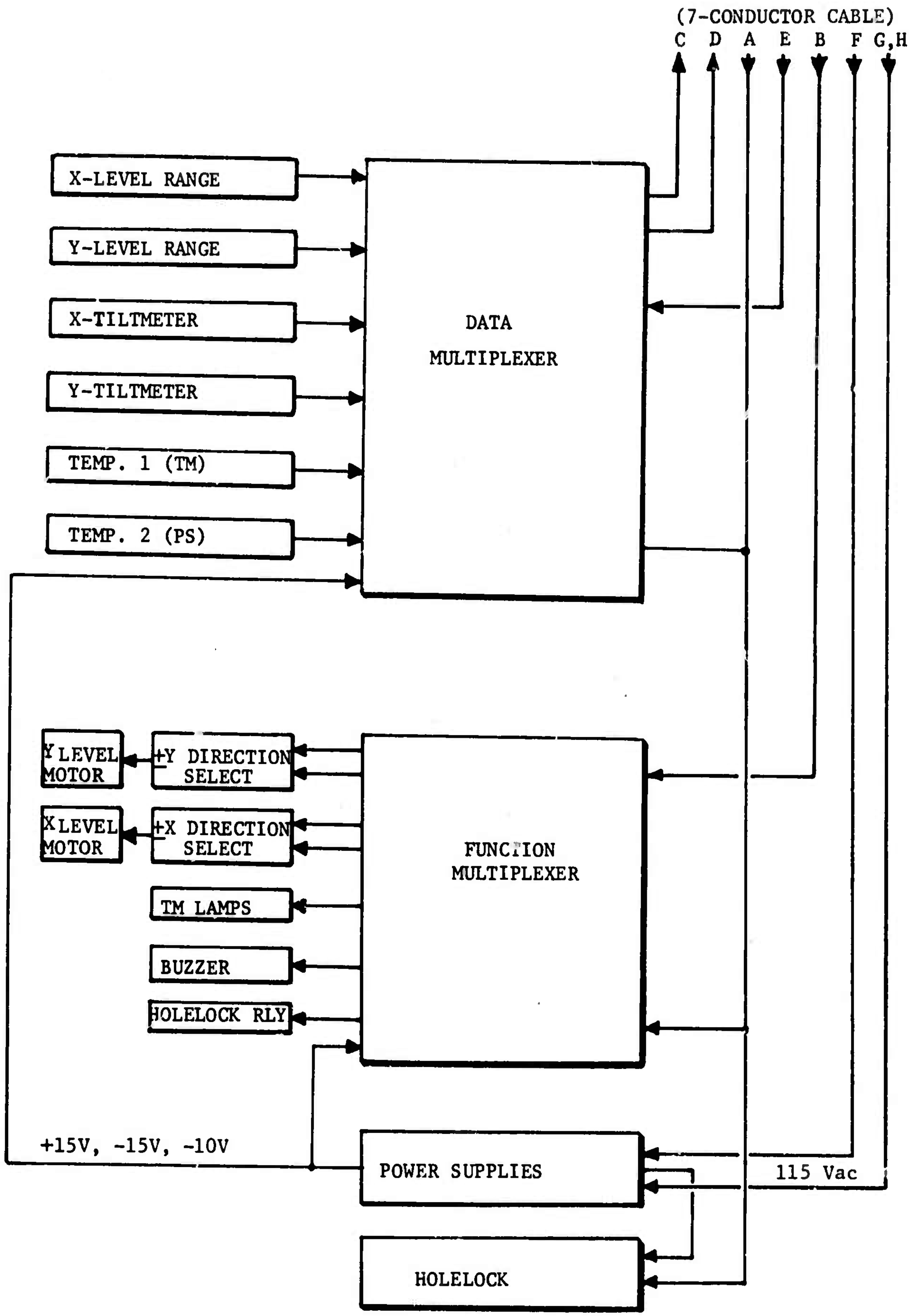

FIGURE 4

Block Diagram of Downhole Electronics

4. Cable Coupling

The cable connector receptacle (Cat. No. MS-2L 8/#16-FCR-P8, 316 S/S from Vector Cable Co., Houston, Texas) was originally provided both for mechanical and electrical connection with the cable. It is pressure tight to 10,000 p.s.i. and has a load bearing capacity equal to the breaking strength of the logging cable used (~ 16,000 lbs.).

However, as we found in preliminary tests, direct coupling of the downhole package to the cable is undesirable because the sway of the stiff, armored cable generates spurious tilt fluctuations (tilt noise). Therefore, we developed a motion decoupler consisting of two chains for supporting the weight and one flexible cable for providing the electrical connection. The flexible cable is actually the neoprene-covered, seven-conductor core of the logging cable, stripped of its double armor over a length of 12 ft.

The chains are mechanically attached to the downhole package by a lifting collar, shown in Figures 1 and 3. The collar is split so that it can be clamped over the groove machined in the top of the downhole package. The two halves are held together by two stainless steel bolts. The upper part of the collar is recessed for the terminal chain links which are pegged to the collar by two captive pins. The collar is keyed to a flat machined in the top of the package so that it fits over it in only one position and cannot be rotated about its axis. This is important for fixing the tiltmeter axes in reference to the fiducial mark (1/2 in. dia. hole) on the top surface of the collar.

The lifting collar also provides a grappling surface for retrieval of the downhole package by a fishing tool in case it became lost in the borehole. For this purpose the top part of the collar is tapered (14° included angle) and a thread (8 t.p.i., right-hand) is cut in the taper. Before the fishing tool can be used, the cable and chains must be removed from the borehole. In order to assure a clean break at the top of the borehole package, the terminal links of the chains adjacent to the collar are reduced in cross section so that they would break before the rest of the chains and the armored cable.

5. The Cable

The cable is a seven-conductor, well-logging cable of the type 7-46 NT made by Vector Cable Co. The armor was made of type 316 stainless steel wire on special order. The conductors are #20 AWG stranded copper wires with polypropylene insulation, embedded in semiconductive neoprene rubber jacket. Each conductor has a resistance of 10 ohms per 1,000 ft. at 25°C. The insulation is rated 1,000 volts, max. The cable has a nominal outside diameter of 15/32 in. and it weighs 367 ft. per 1,000 ft. (in air). The nominal breaking strength of the cable is 16,000 lbs.

The double wire armor is in two layers wound in opposite directions with lay angles chosen so as to approach the torque-balanced condition. However, loading tests made on samples from the cables made to our order indicated that the weight of the downhole package would produce a rotation of more than two full turns per 1,000 ft. of length of cable. Untwisting of this amount of rotation might cause entanglement of cable, if it were rigidly connected to the locked package and allowed to slacken.

This risk was eliminated by using the decoupling chains. The two parallel chains are 10' 1" long and they are connected to the cable armor by a custom-made termination attached by the manufacturer; at the lower end they are connected to the lifting collar as described in the preceding section. The flexible extension of the cable core is coiled between the two chains and is wired to them at 1 ft. intervals to prevent entanglement and possible pinching-off when the downhole package is being pulled up. The lower end of the flexible extension has a connector (Cat. No. MS26 8/#16-CCP, Vector Cable Co.) molded onto the cable for pressure-tight connection with the bulkhead connector on top of the downhole package.

The chains are made of 3/8 in. dia. stainless steel bar and each has a proof test load of 5,500 lbs. The terminal links have a reduced section calculated to lower their proof test load to 2,700 lbs. (each).

Two lengths of cable (2300 and 5300 ft.) were purchased and wound in the factory under proper tension on the two sections of the drum of a power winch built for the purpose by the Drilling Unit of the Army Corps of Engineers in Mobile, Alabama (see photo, Figure 5). The winch has a 40-horsepower gasoline engine and provides power drive for winding up only. Ride down is by gravity and the speed is controlled by a clutch and brake. A cable odometer reading in feet and a tensiometer are provided with the winch.

The uphole ends of the cables are accessible in the space between the two sections of the drum. These ends have no special terminations. However, the seven conductors must be connected to a special connector that fits the input receptacle in the uphole electronics panel. This connector is Cat. No. MS/AN-18-10P made by Amphenol Corp., and its pin designation corresponds to the cable wire numbers as follows:

MS/AN Connector	Cable Wire No.
A	1
B	2
C	3
D	4
E	5
F	6
H	7

The cable wires are numbered clockwise, counting from No. 1 which is the one with yellowish color of the insulation.

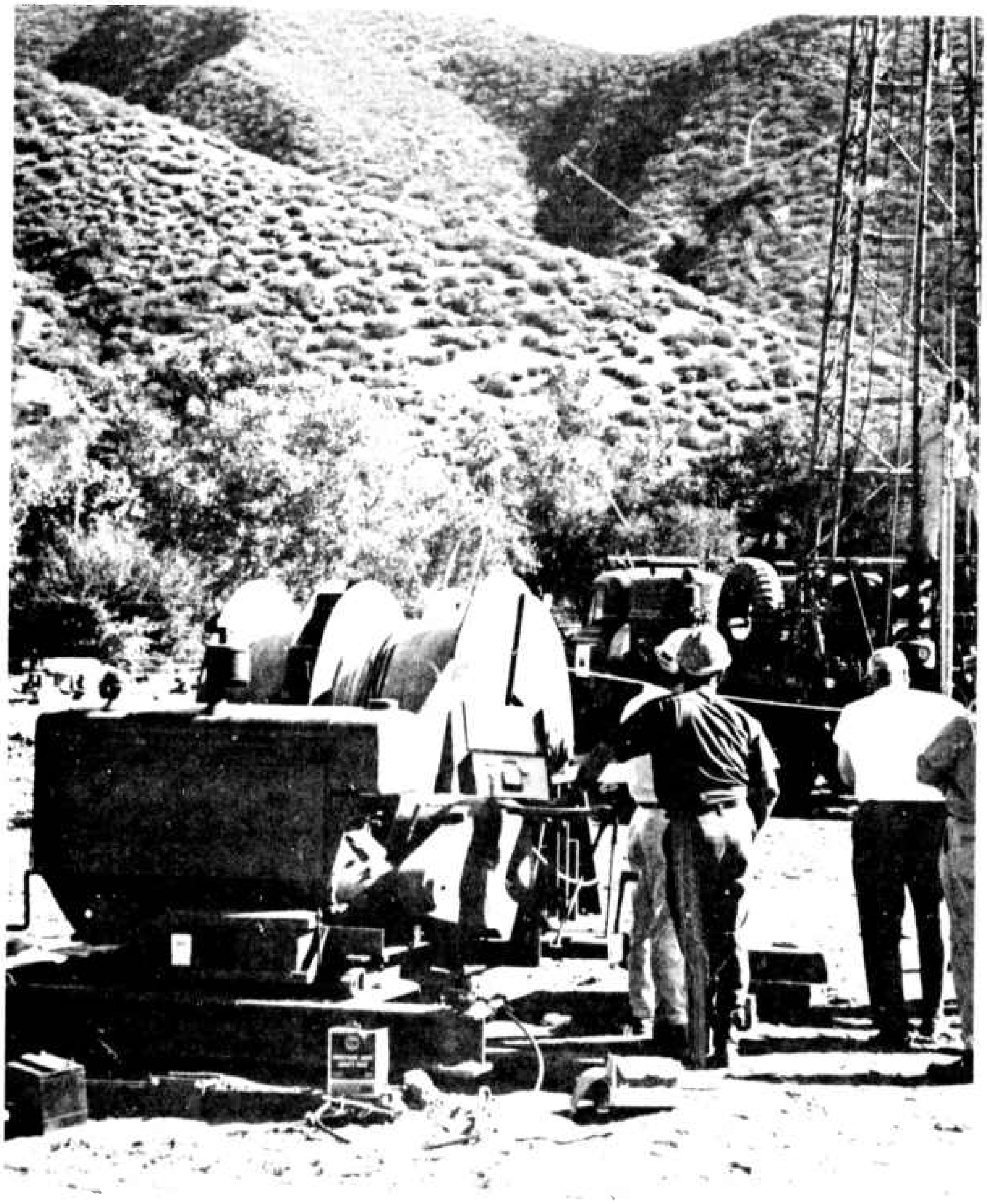

FIGURE 5

Power Winch with Cables

6. Handling and Disassembly of the Downhole Package

Removal of the downhole package from the 2,000 ft. borehole at Stone Canyon is likely to be the first task preceding any change of operation or relocation. The only major piece of equipment necessary for the removal which is not provided with the DBT systems is a crane or rig high enough to support a pulley 24 ft. above the ground. The downhole package is 9.1 ft., the chains are 10.1 ft. and the cable termination is 1 ft. long; the remainder is necessary to clear the well casing (2 ft. from the ground) and to make room for the pulley overhead. Two pulleys are supplied with the DBT system: one is used at the top of the rig, while the other is chained to the well casing to take up the horizontal pull of the cable towards the power winch. The pulleys are 14 in. in diameter and are demountable in order to avoid the necessity for threading the cable through. Other types of pulleys, such as the McKissick pulleys are equally suitable, provided they are at least 14 in. in diameter. The rig or crane used in the operation must have a capacity of at least 2 tons.

The deep hole at Stone Canyon is closed with a cap and a gland seal through which was threaded 450 ft. of the cable remaining of the total length of 2,300 ft. The seal and cap must be removed from the well casing and slipped off from the cable before winding up the cable on the winch. The downhole package cannot be removed from the well without removing the cap. Details of the wellhead, cap, gland seal and cable clamp are visible from the photo, Figure 6.

It is most important to secure the cable to the rig before releasing the gland seal so that it cannot fall into the well by its weight. This is done by means of a cable clamp such as shown in Figure 6 on top of the assembly (two such clamps are provided with the system).

Before the downhole package is hoisted from the borehole, the holelock must be unlocked. This can be done any time, while the cable is still connected to the control electronics. The unlocking is performed by following the procedure outlined in Section II.C.1. Having run the holelock motor in the unlocking direction all the way does not cause the downhole package to fall because the cam is firmly jammed in the casing by the weight of the package. However, as soon as the weight is lifted by pulling up the cable, the cam springs back and the package is free. The package should be pulled up at a speed not exceeding 60 ft./min. When the package is completely out of the casing, it is rested on the ground and secured to the rig in an upright position. The lifting collar is removed and the electrical cable disconnected from the receptacle. The package can be then removed to storage, shipment or disassembly. Lifting of the package separated from the chains and cable is facilitated by using a pair of special tongs supplied with the system; the tongs fit in holes provided at the top of the pressure case.

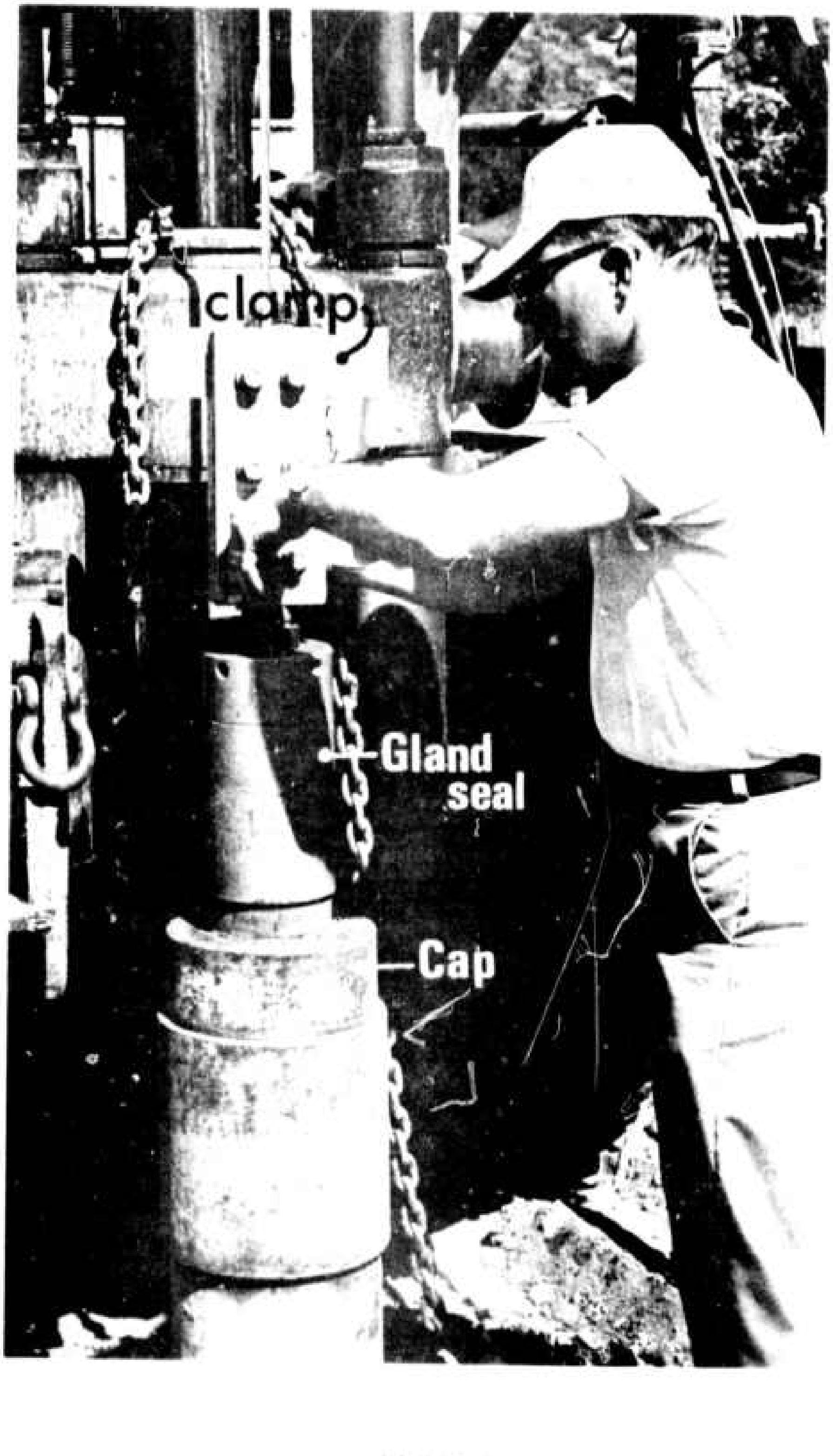

FIGURE 6

Closure of the Deep Borehole with Cable Seal and Clamp

It is not expected that the downhole package will be disassembled by anyone unfamiliar with the details of its construction. However, if disassembly becomes necessary, the following procedure should be followed.

The downhole package is disassembled from the top down. The operation is performed in horizontal position using a special cradle with adjustable rollers which is supplied with the equipment. Special wrenching bars that fit in the spanner holes (1/2 in. in diameter) are also supplied; in addition to these, two strap wrenches and the usual assortment of socket wrenches are needed.

The first part to be removed is the cable connector receptacle. The seven wires internally attached to it are not to be removed. However, the receptacle must be held steady, while the case is being unscrewed from the tiltmeter case so that the wires do not get twisted around the electronics module. Before unscrewing, the package must be carefully aligned on the cradle by the adjustable rollers. The joint to be unscrewed must be refrigerated with dry ice to shrink the Teflon ring seal. When fully unscrewed, the case is slid off approximately 8 in. and the seven-wire bundle is disconnected from the receptacle in the lower part of the electronics module. Then the case is slid off completely and the top cable receptacle with the seven-wire bundle is withdrawn through the top of the case.

Next, the internal electronics module is disconnected and removed from the tiltmeter case to which it is bolted down by four 10-24 screws. Then, the tiltmeter case is unscrewed from the top of the holelock in the same manner as with the electronics case. Before the tiltmeter module is unbolted from the top of the holelock, the two wires coming from the holelock motor must be disconnected. Once the tiltmeter module has been removed, the disassembly is essentially completed.

Individual shipping crates are provided for all components that come apart in the disassembly. They are well suited for shipping by any means of transportation. Tiltmeter modules fit in small wooden cases provided for them. We recommend that these be hand-carried rather than shipped.

We are prepared to service or repair any parts of the DBT system built by Arthur D. Little, Inc. The holelocks should be serviced by the Teledyne-Geotech Corp.

Reassembly should follow, in general, in the reverse order of the disassembly process. Utmost care should be observed in preventing dust, dirt and moisture from entering the tiltmeter and electronics modules and the entire package during assembly. The two Teflon rings in the pressure seals should be replaced by new ones (spare rings are provided with the equipment). These rings are machined to close tolerances and must be handled with care. The grooves in the face seals must be carefully cleaned and no grease is to be used. After the seal is made and the faces are close within a few thousands of an inch, the surface area around the seals is

packed with a few pounds of dry ice in order to shrink the Teflon sufficiently to permit final application of torque by the wrenching bars. The seal faces should come together without a gap and, upon warm-up, the expansion of the Teflon ring completes the seal.

C. UPHOLE INSTRUMENTATION

The surface instrumentation of each DBT system consists of the electronics and the recording unit. The control unit is of central importance, since it controls both the downhole package and the recorders. Without it, it is impossible to receive the data from the downhole package. Should the control electronics malfunction for any reason, the data received from the downhole electronics are likely to be vitiated or unreadable. This results from the nature of the asynchronous multiplexing system chosen for transmission of control and data signals over the limited number of cable conductors.

1. Control Electronics

The purpose of the control electronics is to supply power (115 v ac) to the downhole package, to perform various functions in the downhole package and to receive, digitize and print the data received from it. This is being done by stepping either of the two selectors in the downhole electronics sequentially by control pulses sent out by the counters in the control electronics. A block diagram of the uphole control electronics is shown in Figure 7, and the identification of controls on the panel is shown in Figure 8.

The control panel circuits are energized by operating the switch PANEL and the downhole package by the switch INST. Power at 115 v ac is provided to the package via a Variac to permit partial compensation for line voltage drop whenever a very long cable is used between the panel and the downhole package. The ac voltage on the line is indicated on a panel meter. Since the cable used has a resistance of 10 ohms per 1000 ft. for each conductor and the downhole package draws a current of 0.150 amps, the voltage drop to be made up by the Variac is approximately 3 volts for each 1000 ft. of cable length. The voltage regulators in the downhole package will tolerate a very wide range of ac input voltage. The outputs of the three voltage regulators at +15v, -15v, and -10v are printed out during each print-out cycle to indicate the conditions of the regulators and are also useful as references to check the operation of the entire data multiplexing system at each print-out cycle.

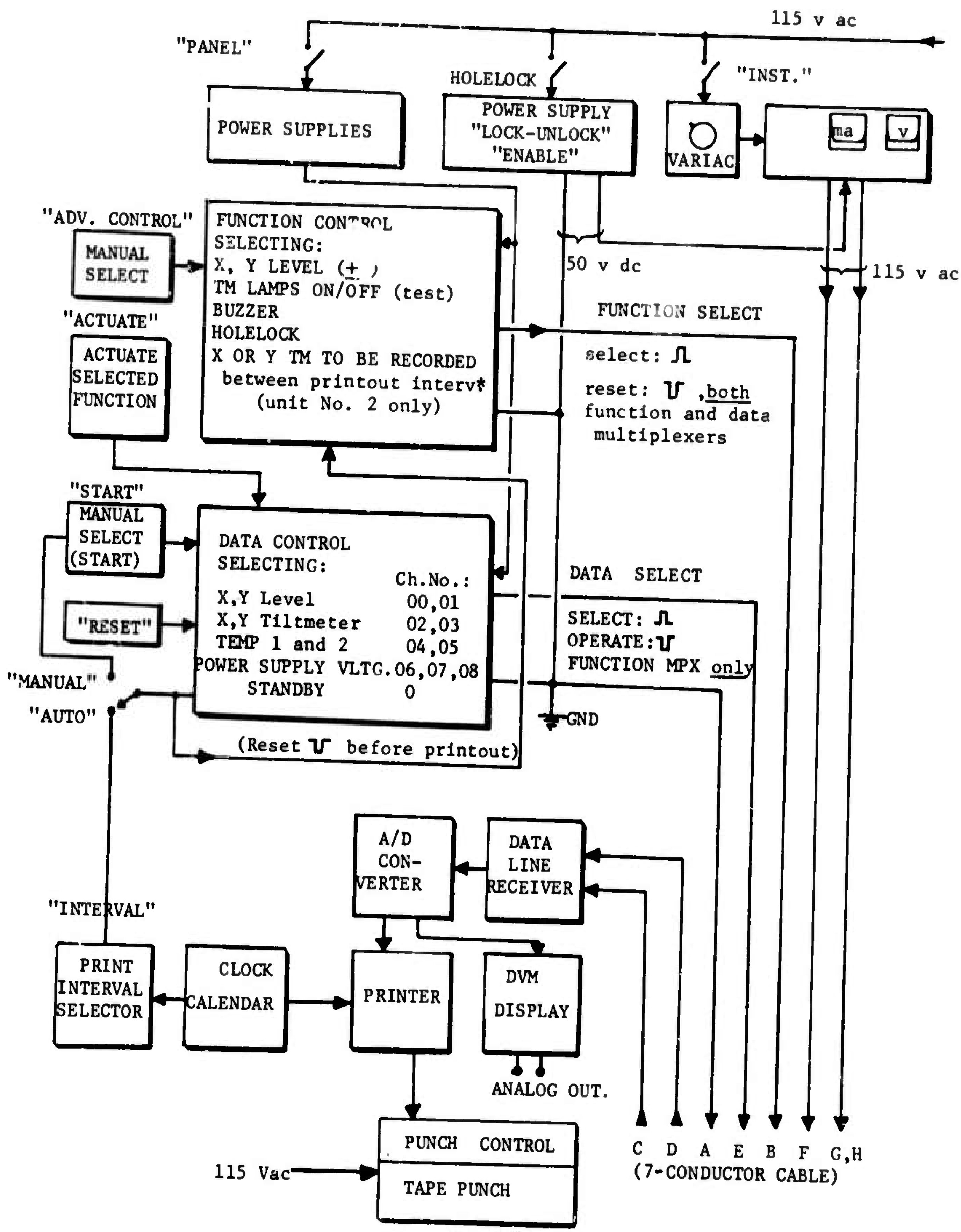

FIGURE 7

Block Diagram of the Control Electronics

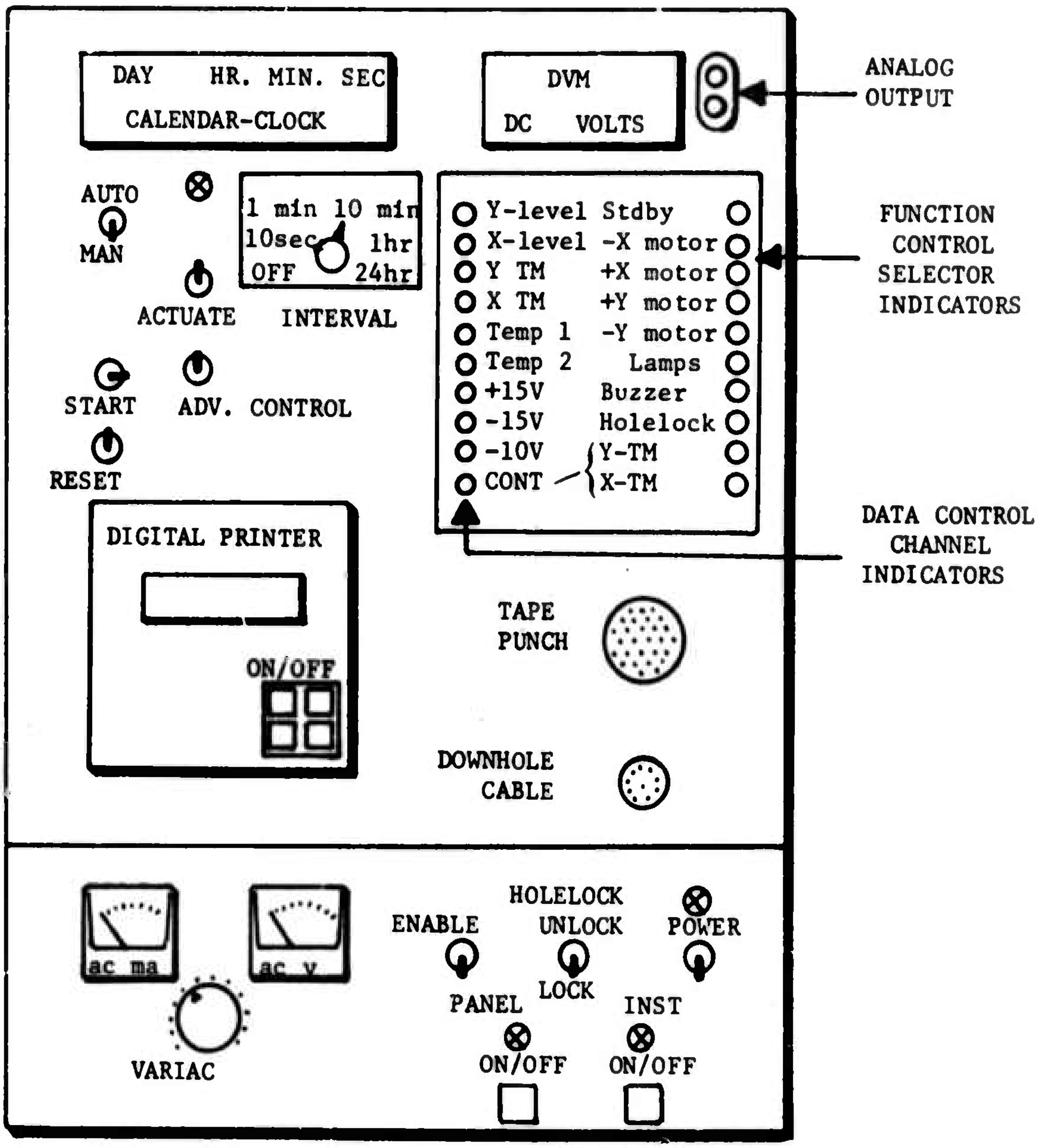

FIGURE 8

Identification of Controls on the Panel of the DBT-2 Electronics

The following functions can be performed in the downhole package from the control panel:

1. remote level in direction +Y

2. remote level in direction -Y

3. remote level in direction -X

4. remote level in direction +X

5. turn off tiltmeter lamps

6. turn on buzzer (vibrator)

7. operate relay to connect holelock

*8. connect Y-tiltmeter for analog recording between print intervals

*9. connect X-tiltmeter for analog recording between print intervals

*The last two operations are provided in the No. 2 unit only.

The control function counters are advanced by means of the ADVANCE switch. The selected function is operated by OPERATE in No. 1 unit and ACTUATE in the No. 2 unit.

The following sequence would be followed to operate the tiltmeter leveling motors:

- set AUTO-MAN switch on "Manual"
- operate RESET switch momentarily to reset counters
- operate START to advance the data control indicators to the tiltmeter of interest
- operate the ADVANCE CONTROL to the desired function as shown by the indicators
- operate the selected motor by means of OPERATE or ACTUATE switch and observe the behavior of the tiltmeter by the digital voltmeter

During this operation the data control selection should be set so that the output of the tiltmeter that is being leveled can be monitored by the digital voltmeter (DVM) on the control panel. In the positions

"X-level" or "Y-level" the DVM will indicate only + or - 5 volts, if the tiltmeter is off level. The leveling motor is then operated in a direction of opposite sign until the indicated voltage drops to zero. This is a coarse indication that the tiltmeter is near its level position. The data selection control is then advanced so that the output of the tiltmeter which is being operated is connected to the DVM. The fine adjustment of the level is then completed by judicious operation of the leveling motors.

The X and Y leveling mechanism interact to some extent so that the leveling of one tends to unlevel the other. Leveling of the two tiltmeters is accomplished by an iterative process and therefore, it is not worthwhile to accurately level one tiltmeter before the other is brought to nearly final level also.

Another function that may be required is the operation of the holelock. This is performed as follows:

- set AUTO-MAN switch on "Manual"
- turn holelock POWER switch on
- operate RESET switch momentarily to reset counters
- operate START to advance the function control indicators to holelock
- select LOCK or UNLOCK position on LOCK-UNLOCK switch
- operate the function by the ACTUATE switch
- turn on the holelock ENABLE switch. In this position the ac milliammeter will be indicating the holelock motor current (approximately 40 ma). The operation takes approximately eleven (11) minutes to complete. At the end of this period the motor opens a limit switch, and the current drops to zero.
- turn off holelock ENABLE switch and the POWER switch
- reset counters with RESET switch and start normal operation of the system

The holelock activation has a separate power supply (50 v dc) for the holelock motor and is contained in a separate panel included with the electronics control unit.

The selection of the data channels can be made automatically or manually. In each case every selected channel is printed out whenever the corresponding voltage is connected by the multiplexer to the DVM.

When AUTO-MAN switch is switched to automatic, the print-out cycle is initiated by an output from the digital clock at intervals selected by the read-out INTERVAL selector switch. When the automatic cycle is initiated, the counters controlling the data multiplexers and control selection are "reset"; the printer advances paper three or four lines and a "trigger" pulse is transmitted to the analog-to-digital (A/D) converter which initiates an internal digitizing cycle. At the end of the digitizing cycle the A/D converter transmits the "End of Conversion" (EOC) pulse to the data control card which transmits a "hold" signal to the digital clock and the A/D converter and a "print" signal to the printer. At the same time, it advances the data multiplexer counters in the panel and in the downhole package by one step. When the printer has printed one line, it advances the paper and transmits the "End of Print" (EOP) pulse to the data control card which begins the A/D cycle again. When the last channel is selected, the EOP pulse is blocked, and the next A/D cycle is not begun until a new sequence is originated by the clock or by the START switch (manually). Note that at the end of the automatic sequence the display is switched to channel 09. Operating the RESET switch resets the data and the function control counters.

Channel 09 is not connected in unit No. 1. In unit No. 2, channel 09 connects to either the X or the Y tiltmeter, as selected by the function control for analog recording. Channel 09 is the "home" or standby position for the automatic cycle.

Each triggered automatic cycle of the data control system "clears" the function control counters in the panel and downhole circuits so that no function is selected. The purpose of this is to reduce the likelihood of accidental operation of any of the downhole functions.

When AUTO-MAN switch is switched to the manual mode, actuating the START switch advances the data control counter. The voltage corresponding to the channel to which counter has advanced is printed out, and the counter stops. The channel remains connected to the DVM, thus permitting the channel to be monitored continuously until the counter is advanced manually again. In this mode the INTERVAL selector switch must be in the "OFF" position, and the multiplexers must be started from the "reset" position which is accomplished by operating momentarily the reset switch. When AUTO-MAN switch is in the manual position and INTERVAL switch is not in the "OFF" position, the system will print the displayed data and advance the data counter one channel at each selected time interval.

The two control units supplied with the systems DBT-1 and DBT-2 differ slightly in the selection of components and layout of panels, as seen in Figure 14. Their function and modes of operation, however, are identical, except where specifically pointed out in the present description. Nevertheless, we recommend that control unit No. 1 be used with the No. 1 downhole package and No. 2 control unit be used with No. 2 downhole package.

Both control units suffer from a difficulty inherent in the asynchronous sequential multiplexers, i.e., transposition of output data when the surface and downhole selectros get out of step. The tendency for this to occur is increased when the control units are operating at low emperatures (close to freezing point). We found that the No. 2 control unit. as installed at Stone Canyon, with two miles of Spiral-4 cable added to the 2300 ft. of downhole cable, tends to malfunction frequently, even at normal ambient temperatures when operated in the automatic mode. At present, it functions properly only when operated manually by printing out the output data, one channel at a time.

2. Recording Systems

Each control electronics unit contains a built-in digital printer (Digitec Corp., Mod. 691 with Nos. 691-2 and 691-3 input cards) for recording the data. A sample of printout from the DBT-2 system is shown in Figure 9 with pertinent explanations. The voltages printed out are in millivolts (the symbol "dcV" should read "dcmV," but this symbol was not available). Printout from the DBT-1 control unit is in the same format, only the voltages are printed with the decimal point shown correctly for "dcV."

In addition to the built-in printers, the control electronic units provide outputs for external digital tape punch units. The tape punches used are Digitec Mod. No. 671 (with controller Mod. No. 623) with system DBT-1 and Mod. No. 672 (with controller Mod. No. 625) with system DBT-2. The Mod. No. 672/625 tape punch differs from the 671/623, mainly in its larger tape capacity (1500 ft. of 1 in. tape). The punches with their controllers are housed in cabinets separate from the control electronics, as shown in Figure 14. Special multiconductor connecting cords with 64-pin cable connectors are provided with the control electronics.

The punch controller converts the parallel BCD output of the DVM to the serial input and drives the punch. Recording on the tape is made in the ASCII, even-parity code in a format readable by a standard teletype console. A reading and listing program for a time-share computer was written and is available. Also available is a plotting program for a Hewlett-Packard Mod. HP-7200A graphic plotter.

Day No.	G M T	Channel No.	Channel Output, mV	
029	155321	09	+00015dcV	Empty Channel
029	155320	08	-01022dcV	Downhole Power Supply Voltages
029	155319	07	-01536dcV	
029	155318	06	+01546dcV	
029	155317	05	+00415dcV	Thermistor, Electronics
029	155316	04	+00306dcV	Thermistor, Tiltmeters
029	155315	03	+00042dcV	X-comp. Tiltmeter
029	155314	02	+00018dcV	Y-comp. Tiltmeter
029	155313	01	+00001dcV	X-level Indicator
029	155311	00	+00004dcV	Y-level Indicator

FIGURE 9

Sample of Printout from DBT-2

An external recorder may be connected to the terminals marked "Analog Output" for continuous recording of any one of the selected channels. When analog recording is done with the DBT-1 system, the control unit is in the manual mode and no data can be printed out or recorded as long as analog recording continues. This is a fairly serious limitation which was corrected in the second system. In the DBT-2 system, analog recording of either X or Y tiltmeter outputs is possible, while the operation is in the automatic mode. For this purpose the X or Y tiltmeters (channels 03 or 02) are selected by the function control as described in the preceding section and switched to automatic. In this mode each cycle ends on channel 09 which is connected to either X or Y tiltmeter; thus, analog recording is done during the interval between the periodic printouts. The analog recorder is subjected to a rapid sequence of large (up to ± 15 volt) transients during the printout, which may cause overloading and generation of bad "spikes" on the chart record. In order to eliminate this transient, a special circuit is provided in the No. 2 control panel, which disconnects all circuits from the recorder when the automatic scan is in progress. The output of this circuit ends in a pair of terminals in the lower right corner of the panel marked "Analog Out" and the analog recorder is to be connected there.

A miniature analog recorder (Mod. M-12 by MFE Co. of Wilmington, Mass.) is supplied with the DBT-2 system. This recorder serves more as a continuous monitor than a high resolution instrument, since both its speed (1/2 in. per hour) and its chart width (50 mm) are limited. Its main merit is that it requires practically no attention (it uses inkless recording on heat-sensitive paper, and its chart supply lasts for approximately two months). If higher resolution in time or amplitude is required, a suitable recorder can be used in its place, provided the input impedance is greater than ~ 50 kilo-ohms.

Caution is to be observed in connecting the external recorder lest any spurious voltage (ac or dc) higher than approximately 20 volts be accidentally applied to the terminals. While the DVM itself is protected against overvoltage (up to 500 v) the instrument amplifier (Burr-Brown Co., Mod. 3165/25), which feeds the DVM, is not protected and could be damaged.

3. Calibration Curves

All data transmitted from the downhole package and recorded on the surface are in volts (or millivolts). They are translated into the corresponding physical quantities by means of the calibration curves reproduced in Figures 10 and 11. The tiltmeter modules were calibrated in the laboratory using a standard tilt table. The accuracy of tilt calibrations is believed to be of the order of 5 percent. The output of the diamagnetic tiltmeters was found to depend on the temperature and, consequently, the calibrations had to be made over a range of temperatures corresponding to that which might be encountered in field use. The results of these calibrations are presented as a set of curves in Figure 10.

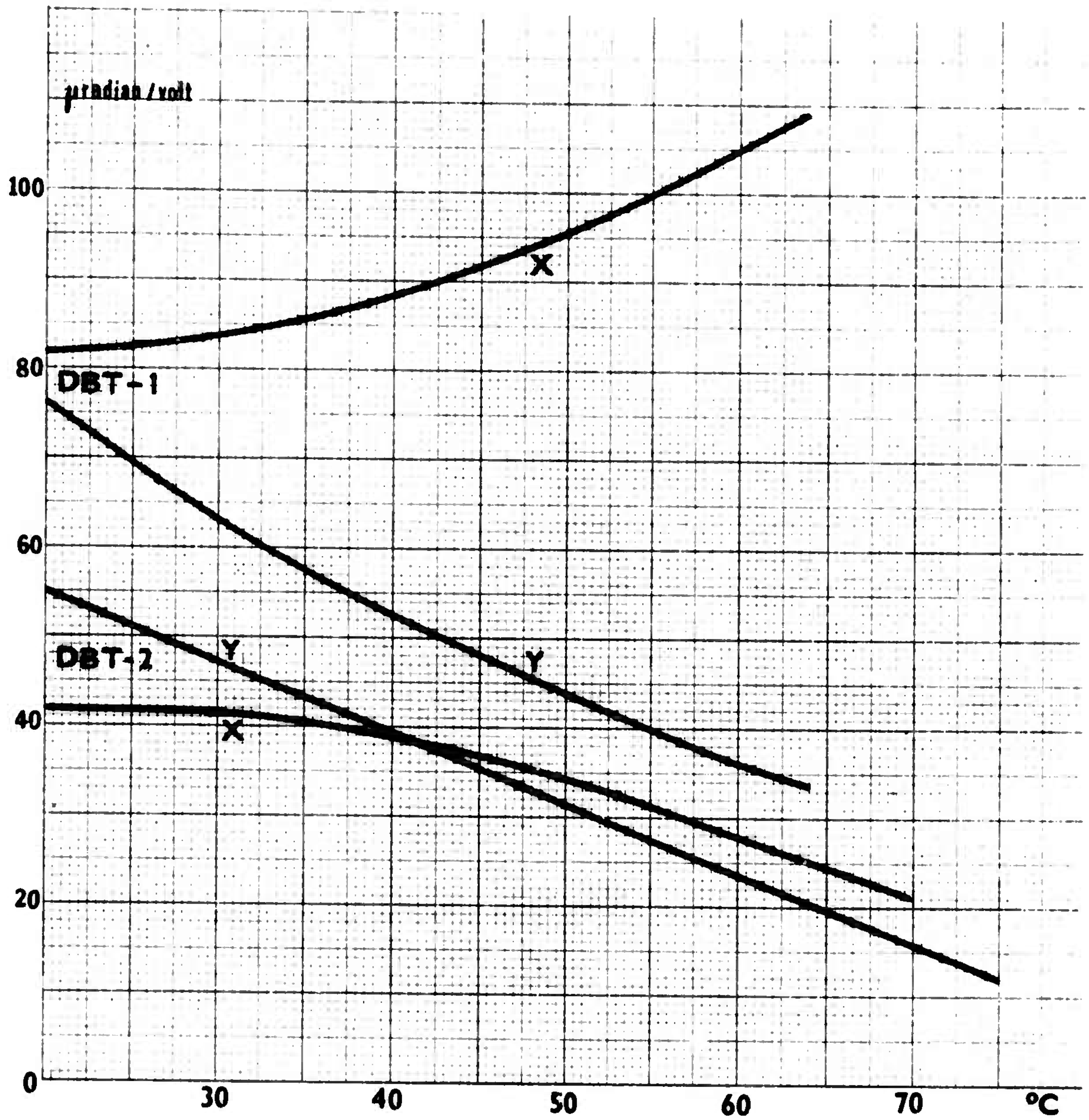

FIGURE 10

Tiltmeter Calibration Curves for DBT-1 and DBT-2

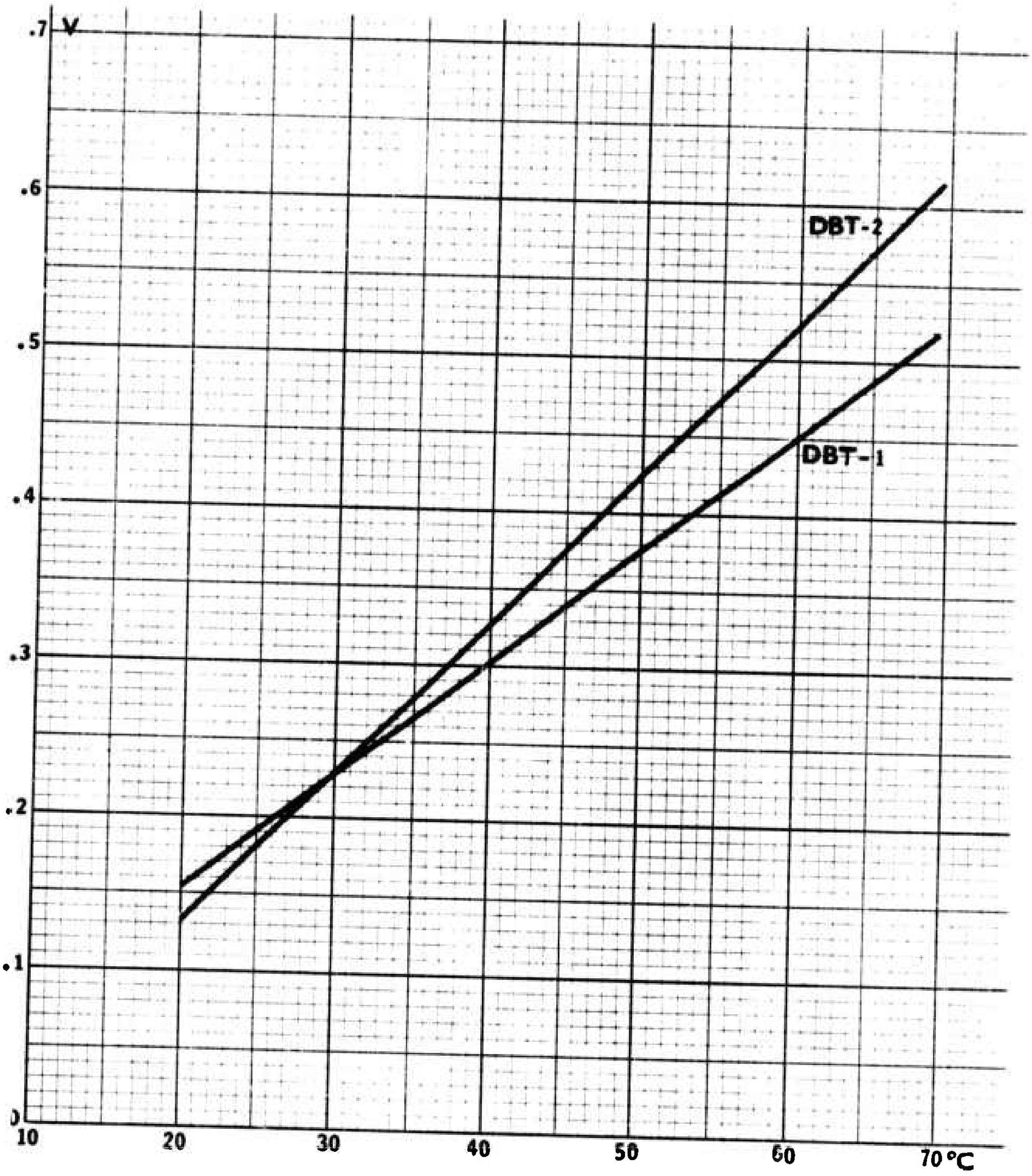

FIGURE 11

Calibration Curves for Temperature Sensors in the Tiltmeter Modules

In order to make use of these curves, the operating temperature of the tiltmeters downhole must be known. The temperature in the tiltmeter modules is measured by temperature sensors which are attached to the metal frame. Their calibration curves are shown in Figure 11. Since they are very nearly straight lines, the response of the temperature sensors may be described by constant coefficients having values of 7.2 mv/°C in DBT-1 and 9.6 mv/°C in DBT-2. Another set of temperature sensors is provided in the electronics modules. Their calibration constants are approximately the same as those of the tiltmeter modules. The temperature sensors in the electronics modules serve mainly the purpose of checking whether the operating temperature of the electronics are within safe limits (below 125°C). In borehole use, the temperature in the electronics module is, typically, 10°C above the temperature in the tiltmeter module. The latter is estimated to be no more than a few degrees above the temperature of the outside.

The last set of curves presented in Figure 12 represents the apparent zero shift of the tiltmeters in the DBT-2 system. (A corresponding set for DBT-1 is not available.) Even though the zero shift appears to be appreciable (.5 to 1.0 μrad./°C), it is expected to be of small consequence in actual use, since the temperature in the borehole is, under normal conditions, varying only very slowly and is being recorded at all times.

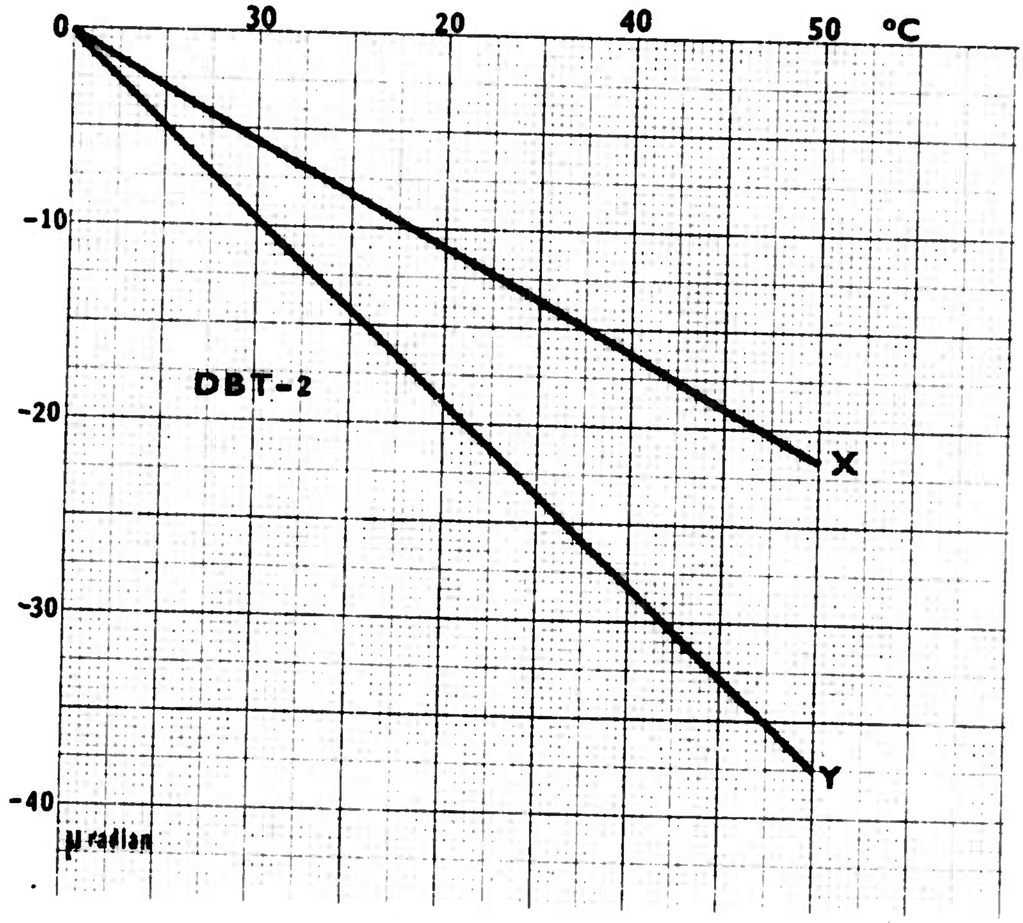

FIGURE 12

Apparent Zero Shift of the Two Tiltmeters in DBT-2

III. FIELD EXPERIMENT AT STONE CANYON

Experimental application of the two completed deep hole tiltmeter systems was originally planned for studying earth tilts in oil fields subjected to water injection, such as at Rangely, Colorado; Baldwin Hills, California; and Santa Fe Springs, California. However, negotiations for the release of wells in any of the three fields were fruitless. Meanwhile, we were advised that a borehole to be drilled at Stone Canyon, California (for another experiment sponsored by ARPA) will become available for some period of time, until the other experimental equipment (deep hole strainmeter) is ready. This appeared to be a very good opportunity, and we accepted the offer to install the tiltmeters there.

A. THE SITE

The Stone Canyon is in San Benito County, 11 miles south from Paicines in Central California. Its elevation is 1,000 ft. and the surrounding peaks reach elevations 1,500 to 2,200 ft. The site is within the fault zone of the San Andreas fault. The visible trace of the fault lies approximately 1.2 miles northeast from the site. The site was selected for being located in the granitic massif of the Gabilan Range, which extends to the west and northwest of the fault.

The segment of the fault in the vicinity of the site is seismically very active. A strong tremor was felt at Stone Canyon on September 2, 1972, and a sequence of earthquakes occurred on October 2, 1972, at the site and at San Juan Bautista, 30 km NW from the site.

The site is approximately 1.5 miles west from the Stone Canyon Seismological Observatory established and maintained by the Earthquake Mechanism Laboratory of NOAA at San Francisco. The Observatory operates a local seismic array and a number of surface instruments including strainmeters and tiltmeters. We have been offered shelter and power connection for our equipment by Dr. Don Tocher, Director of EML. Mr. Daryl Sheldon kindly agreed to operate the recording equipment we installed in the observatory.

The boreholes at the site have been drilled on a two-acre lot leased from Mr. Hannes Schroll, owner of the 101 Ranch, Paicines. The permission to perform the drilling and to enter the property is covered by a lease executed by the District Engineer, U. S. Army Engineer District, Sacramento, Real Estate Division, November 1, 1971. The existing lease provides an extension through October 31, 1973.

A jeep road, passable (in dry weather) by almost any kind of vehicle, leads from the ranch gate on Rte 25 to the site. The road is normally closed by a padlocked gate. The site is enclosed by a (somewhat marginal) wire fence and a locked gate. There is no power line nor telephone line to the site; however, two diesel-generator sets have been installed by the U. S. Army.

B. BOREHOLES

Two boreholes have been drilled at the site, one 2,080 ft. deep and another 40 ft. deep. Both were designed and produced by the U. S. Army Engineer District, Mobile, Alabama, under agreement with the U. S. Air Force Office of Scientific Research. The original plans were developed and the operations supervised by Mr. David F. Childers of the Mobile Engineer District. After his retirement the project was completed under supervision of Mr. Charles H. Cox of the same District. The driller was Mr. R. D. Jones (until June 30, 1972) and later Mr. H. P. Herman until completion of the project, October 1, 1972.

The deep hole was originally planned for the strainmeter under development by the Develco, Inc., of Mountain View, California. This instrument is to be permanently cemented to the rock at the bottom of the borehole. For this reason the lowest 90 ft. of the borehole are uncased, while the rest is cased all the way to the surface. The tilt-meter is locked to the casing well above the uncased section.

The deep borehole is cased with a 9.00" I.D. -- 9 5/8" O.D. casing from the surface to the depth of 1,240 ft. and from there down to 1,990 ft. with a 8 5/8" I.D. -- 9 5/8" O.D. casing. A constriction (coupling) of 8 3/4" I.D. is located at 690 ft. below surface, due to a break in the casing. Casing was cemented (by the Halliburton Co.) over the full depth to the rock which was reamed out to 12 1/4" I.D. Deviation of the borehole was logged by the Eastman Co. and found to be less than 2° 15' (the maximum value at 1,575 ft.). A velocity log was made by the Bird-well Div. of S.S.C.

The hole was initially cored with a NQ size drill to a depth of 1,818 ft. A detailed coring log was written by J. H. Bryan, geologist, and is on file with the Mobile Engineer District. Based on the core log and the velocity log, we can describe the nature of the rock downhole as follows:

- the overburden (sand, gravel, boulders) reaches approximately 40 ft. below surface
- the rock is a coarse-grained quartz diorite (40-60% quartz, 25-30% feldspar, 10-20% biotite, 2-5% epidote, and other accessory minerals)
- the rock is weathered to approximately 500 ft. below surface; it is fractured and jointed over the entire depth
- major shear zones marked by presence of fault gauge were identified at approximately 160, 350, 450, 515-565, and 940 ft. below surface
- based on the velocity log, the rock appears to be less fractured and more compact below 1,800 ft.

The completed borehole was scrubbed, washed and bailed. The rate of leakage was estimated at approximately 1 gal./day; this corresponds to the water level rising at a rate of approximately 8 ft./month. On September 27, 1972, the water level stood at approximately 1,800 ft. below surface. The groundwater level at the site was estimated to be at 20 to 30 ft. below surface.

A shallow hole was drilled adjacent to the deep hole for the installation of the "surface" tiltmeter. This hole is 40 ft. deep, with a 9.00" I.D. -- 9 5/8" O.D. casing cemented to the overburden. The hole is cemented at the bottom and is nominally dry.

C. LOGISTICS AND INSTALLATION

After the completion of tests in Cambridge and at Bedford, Mass., the equipment was crated and on September 22, 1972, shipped by air freight to San Francisco. From there, it went by truck to Hollister, California, where it was reloaded on Army trucks for transport to the site. The list of the equipment shipped and delivered to Stone Canyon is shown in Table II. The total gross shipping weight was 1,100 lbs. and the total volume was 84 cu. ft.

The equipment was stored in a shed at the site. This prefabricated metal structure (Figure 13) is the only building on the site. It is erected on a concrete slab, has a floor area of 9 x 12 $ft.^2$ and is 6 1/2 ft. high. It is provided with six electric power outlets (115 v ac) connected to a diesel generator set up in a fenced-off enclosure adjacent to the shed. The Army initiated negotiations with the Hollister Office of the Pacific Gas and Electric Co. for bringing a power line to the site. No action was taken on this, however, at the time of the installation and the power was provided by an auxiliary generator set when needed.

Since the shed was rather crowded with crates and equipment, the assembly of the downhole units was done on a bench set up outside, under a canvas shade. Care was taken to stop all operations that would generate dust during the critical steps of the assembly. The dry ice required for the assembly of sealing rings was brought from an ice plant at Watsonville (approximately 35 mi. north from the site). Once the assembly of downhole case and seals was finished, the rest of the mechanical assembly operations were completed on the ground or on the rig. The electronics systems were assembled in the shed and set up, as shown in Figure 14.

TABLE II

LIST OF EQUIPMENT DELIVERED TO THE STONE CANYON TEST SITE

Crate No.	Item
1	Control Electronics No. 1 (DBT-1)
2	Tape Punch No. 1
3	Downhole Tiltmeter Case No. 1
4	Downhole Electronics Case No. 1
5	Tape Punch No. 2
6	Control Electronics No. 2 (DBT-2)
7	Downhole Electronics Module No. 2
8	Downhole Electronics Module No. 1
9	Downhole Tiltmeter Case No. 2
10	Downhole Electronics Case No. 1
11	Two 14-inch pulleys, four chains, two clamps, assembly fixtures and tools
13	Holelock No. 1
14	Holelock No. 2

NOTE: (a) All crates are visibly numbered.

(b) No. 11 is a 55-gallon steel barrel.

(c) There is no crate No. 12.

(d) The logging cables were shipped from the factory.

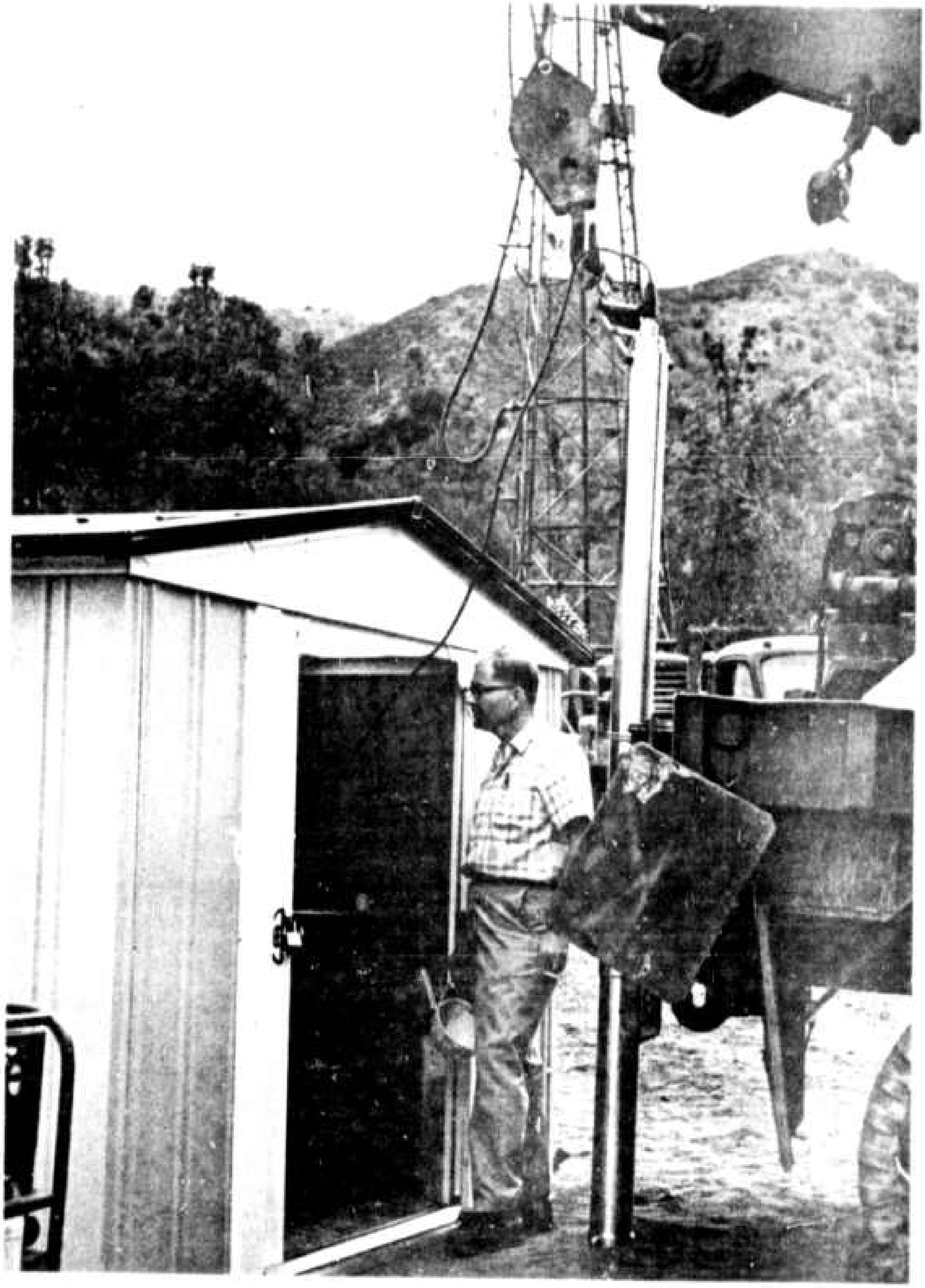

FIGURE 11

R. M. Lucas with Assembled Downhole Package, Watching Check-Out of the Electronics (Inside the Shed)

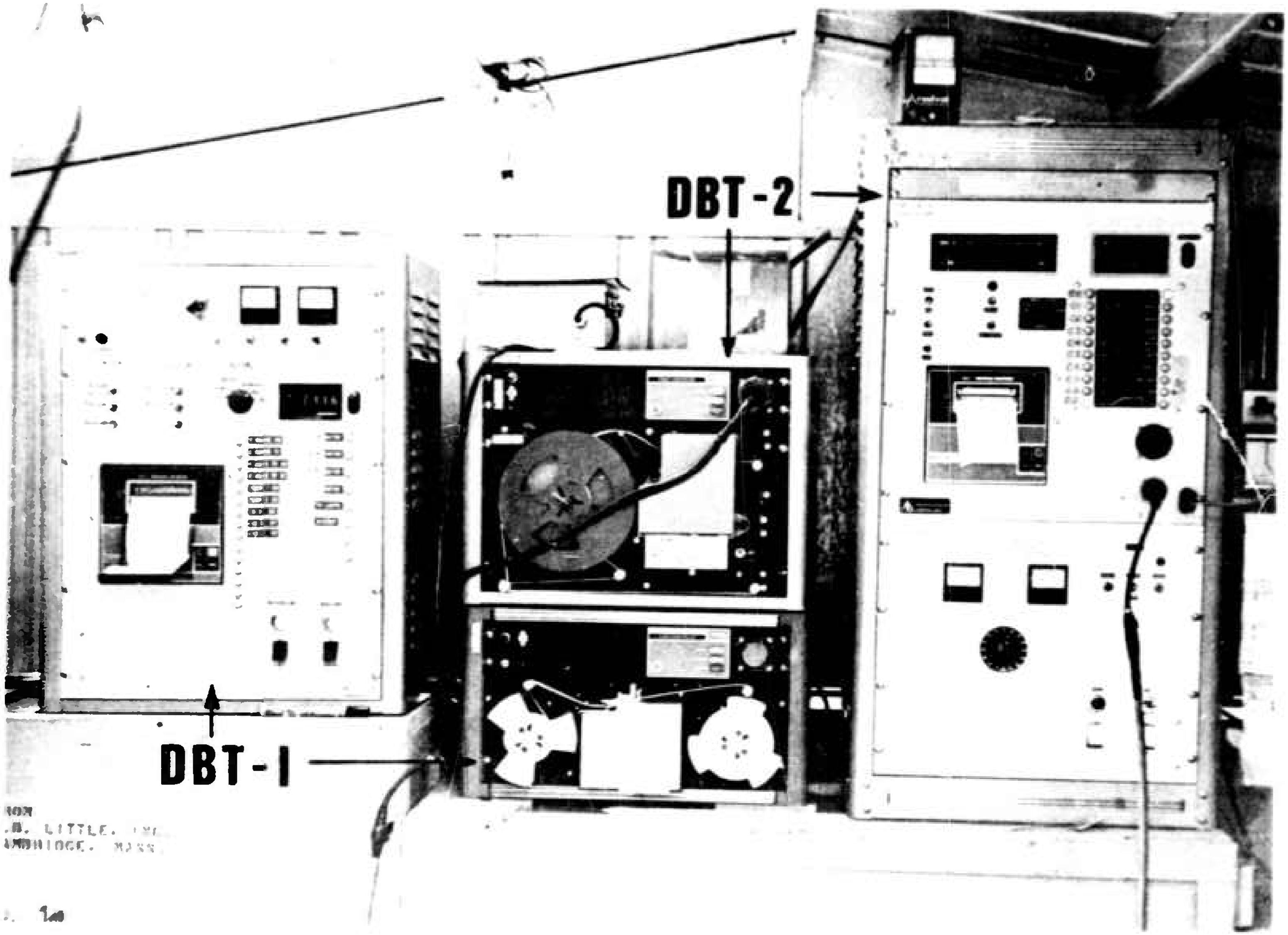

FIGURE 14

Control Units and Tape Punches of Both Systems Installed in the Shed

Work on the site started on September 25, 1972. The DBT-2 system was assembled first, and its downhole package was placed in the deep borehole using the 2,300 ft. cable. The depth at which the package was locked in was 1,862 ft. This depth was selected principally on the basis of the velocity log supplied by the Birdwell Co. At and around 1,860 ft., the velocity of the P-wave was reaching the highest value (~ 5000 m/sec.), and the presence of S-wave reflections was indicating a reasonably solid rock.

In order to assure that the package was set axially straight in the borehole, the cable was pulled up a few feet after the holelock cam was fully extended. Then, the cable was slackened 3 ft. to allow the cable to become decoupled from the package; by this procedure, the cam was firmly jammed in the casing by the weight of the package.

The orientation of the package in the borehole was to be done by a gyro-oriented TV camera supplied by the Omaha, Nebraska, District of the Army Corps of Engineers. To provide a visible target for the camera, a 3 ft. extension rod was inserted in the 1/2 dia. hole serving as a fiducial mark on the top of the package. The top of the rod (actually, a 1/2 in. O.D. fiberglass-epoxy tubing) was provided with a wooden plug painted in a black and white, semicircular pattern.

The camera crew arrived on September 27th with the equipment and started the checkout procedure. When the necessary extension cable was connected to the camera, the gyro control circuit developed trouble and remained malfunctioning despite strenuous efforts of the crew to fix it and to have it repaired at manufacturer's plant in San Diego. Consequently, the downhole package was installed without orientation, with the understanding that the camera will be repaired and will become available later.

The DBT-1 system was assembled on September 30, and the downhole package was placed in the shallow hole and locked in at a depth of 30 ft. The orientation of the package was determined visually by sighting the fiducial mark on top of the cable coupling. The direction was transferred to the surface in reference to a staked-out line. The direction of the + X-axis was determined to be 137°N (true N, which is 17°W of magnetic N at the site).

Both systems operated on the site completely satisfactorily immediately from start up. However, it turned impractical to operate them continually from the generators, since this would require constant maintenance and periodic refuelling every 12 hours.

Therefore, we decided to move the control and recording units from the shed to the Stone Canyon Observatory and operate both systems from the power line at that point. For this purpose we laid four runs of the Army-type, four-conductor cable from the Observatory to the site. This cable (so-called Spiral-4) comes in 1/4 mile lengths with water-tight connectors on both ends. The conductors are #18 AWG copper, unshielded but provided with a steel-wire reinforcement molded in the rubber jacket. Cable of 8 1/2 lengths (2.125 miles) was used in each run. The total resistance

per pair of conductors in each run was approximately 140 ohms. Since the current for the downhole package is approximately 0.15 amp., the voltage drop in the power supply pair of conductors was 21 volts. To this was to be added the voltage drop in the logging cable, which was, for the No. 1 package (5300 ft. cable) 16 volts and for the No. 2 package (2300 ft. cable) 7 volts. These volage drops were made up by the Variac boosters on the control panels.

A view of the DBT-2 control panel with its tape punch and the analog recorder, as installed in the Observatory, is shown in Figure 15.

D. PRELIMINARY RESULTS

Regular operation of both systems started on October 1, 1972. System DBT-1 was started in the automatic mode on one-hour cycle with tape punch for digital data recording. It operated continually until October 17 at which date the punch controller started to malfunction and eventually broke down; the control unit No. 1 was then turned off. System DBT-2 was also started in the automatic mode, and it is operating in this manner to date. The quality of data started to deteriorate, however, and eventually the automatic printouts became unreadable; consequently, the tape punch was turned off, but the control panel was left on. After October 6, good data were obtained from DBT-2 only by manual operation, printing out the channels one by one; the analog recorder was operating satisfactorily all the time.

In spite of these difficulties, operation of both systems yielded some interesting results. The following figures illustrate the general nature of the tilt recordings obtained to date. Figure 16 shows the machine plot of the X and Y components of tilt and the temperature in the shallow hole (DBT-1) for the first week of operation. Fortuitously, a number of seismic events occurred on a second day of operation (Monday, October 2, 1972), which were recorded by both systems.

A local earthquake at Stone Canyon (m = 1.7) was recorded at the Observatory at 2354 GMT, and three events centered near San Juan Bautista (30 km NW of STC) were recorded later that day: m = 2.9 event at 0559, m = 4.9 at 0630, and m = 4.1 at approximately 1110 GMT. Analog recording of these events in the Y-component of tilt in the deep borehole is shown in Figure 17. Sudden and large offsets in both components of tilt in the shallow borehole seem to coincide with these events. No corresponding offsets were recorded by the deep hole tiltmeter.

However, in the following months, the deep hole tiltmeter recorded several large tilt steps, not associated with any local seismic events. This is shown in Figures 18 and 19, summarizing the manually recorded data from DBT-2 in the form of an X-Y plot of the tilt vector. A similar plot from DBT-1 in the shallow hole is shown in Figure 20. Unfortunately, the latter ends by October 17, and thus does not allow comparison with Figure 18 for the period of large tilt offsets in the deep hole.

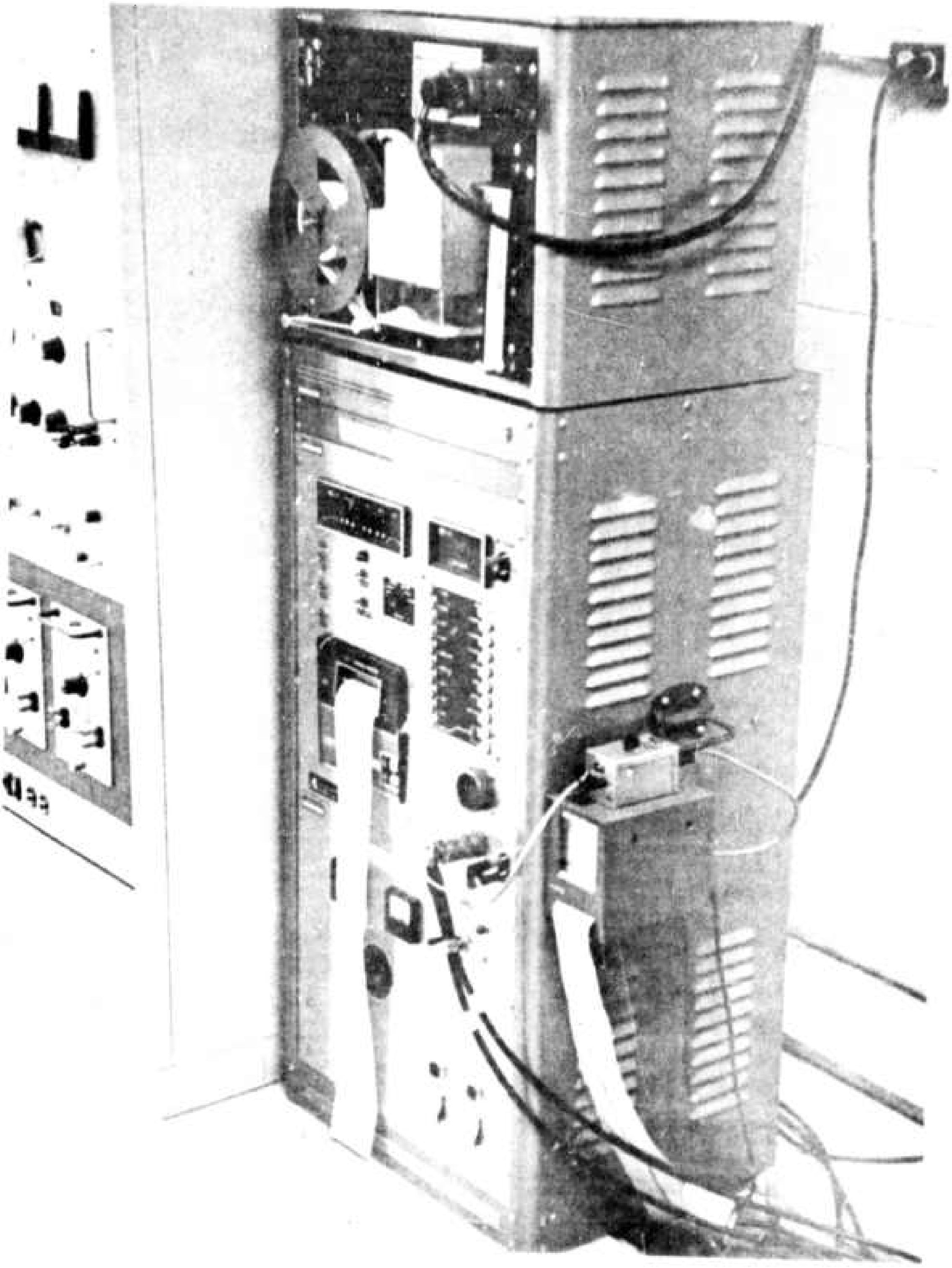

Figure 15

DBT-2 Control Unit, Tape Punch and Analog Recorder [illegible]
In the Stone Canyon Seismological Observatory [illegible]

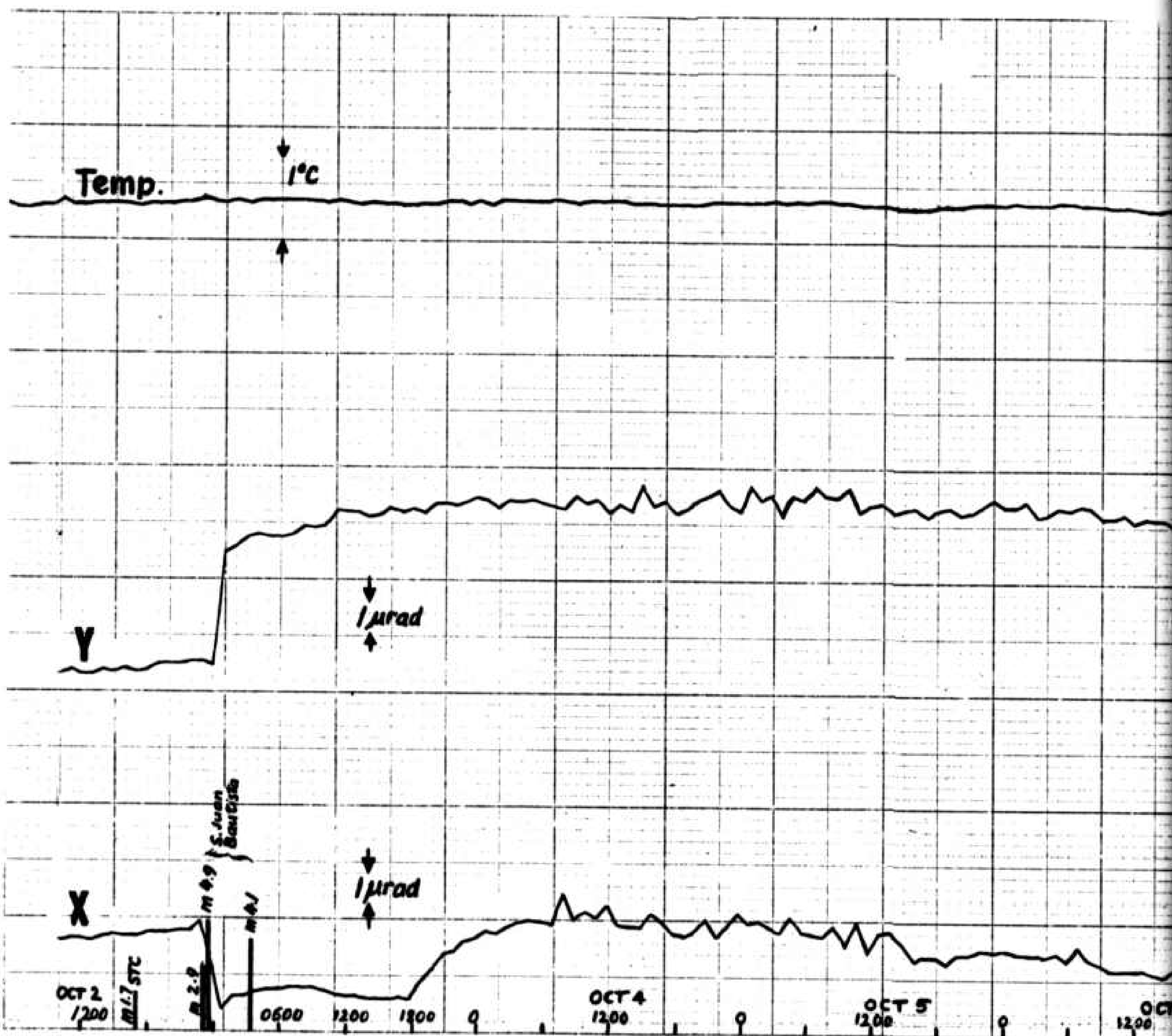

FIGURE 16

Hourly Plot of X and Y Components of Tilt from

in the Shallow Borehole

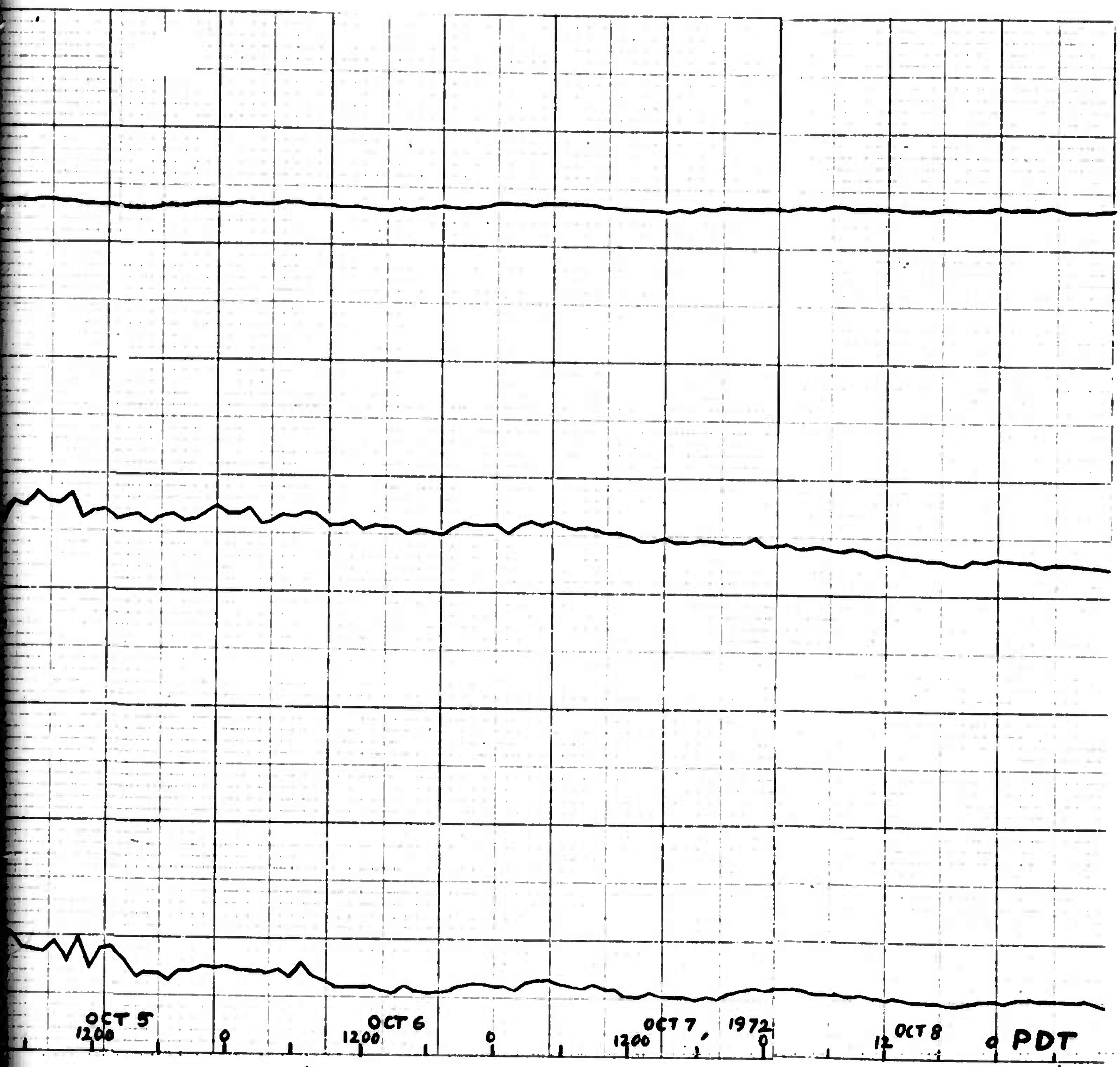

FIGURE 16

f X and Y Components of Tilt from DBT-1

in the Shallow Borehole

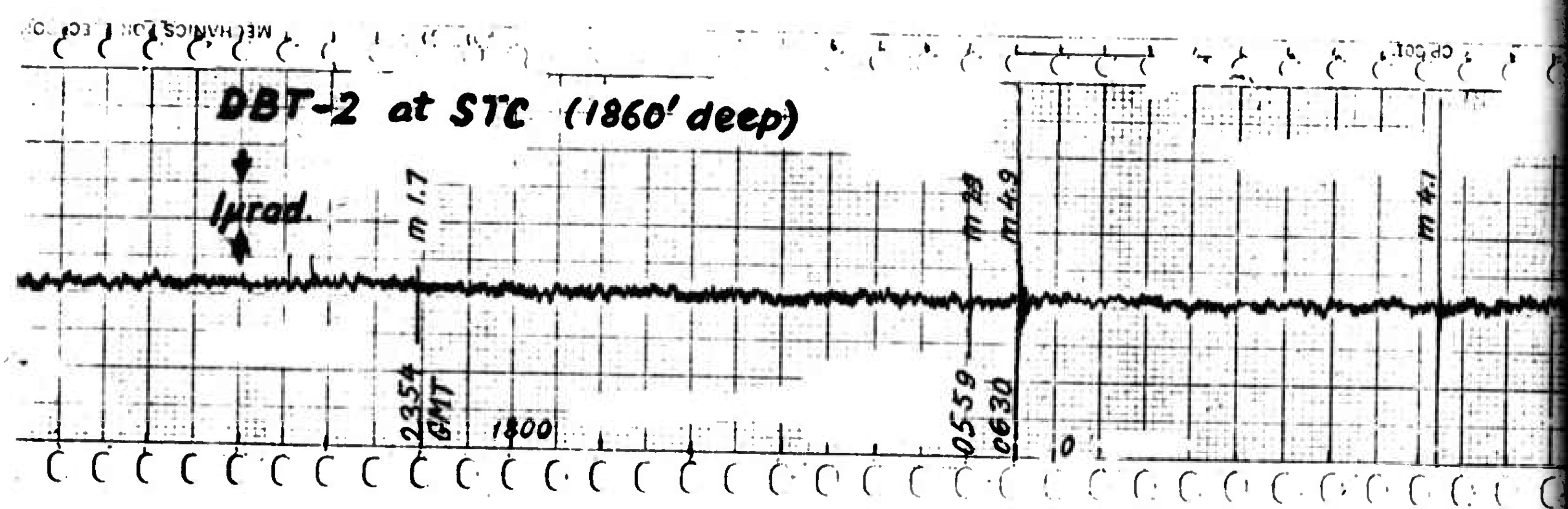

FIGURE 17

Analog Record of the Y-Component of Tilt from DBT-2 in the Deep Borehole

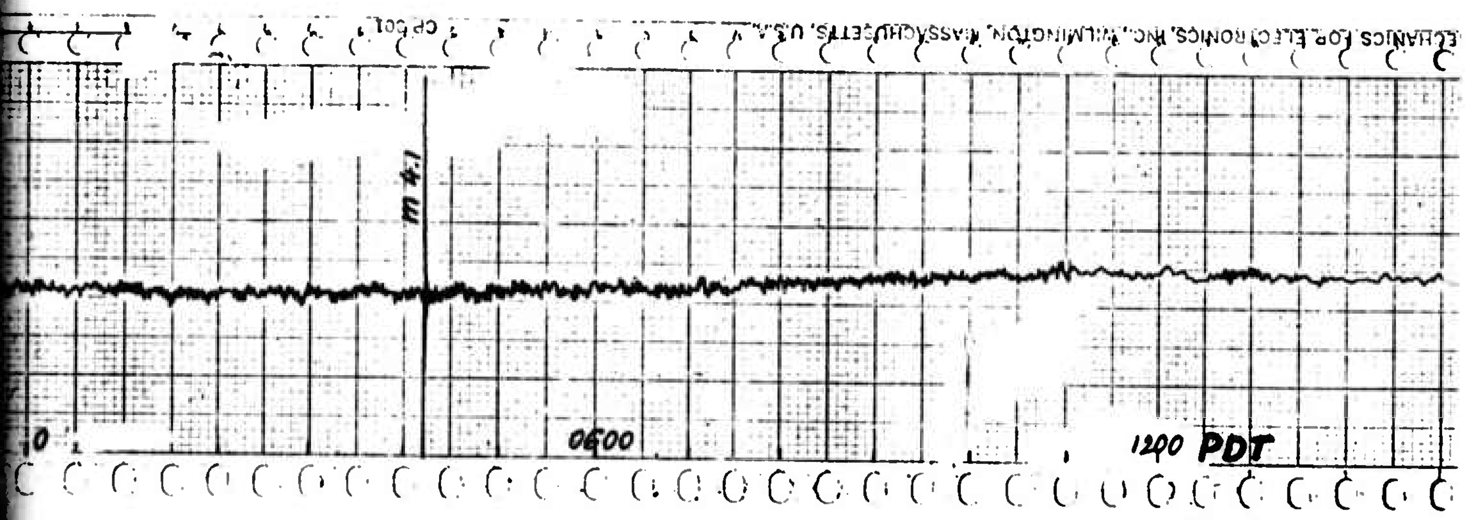

FIGURE 17

cord of the Y-Component of Tilt

DBT-2 in the Deep Borehole

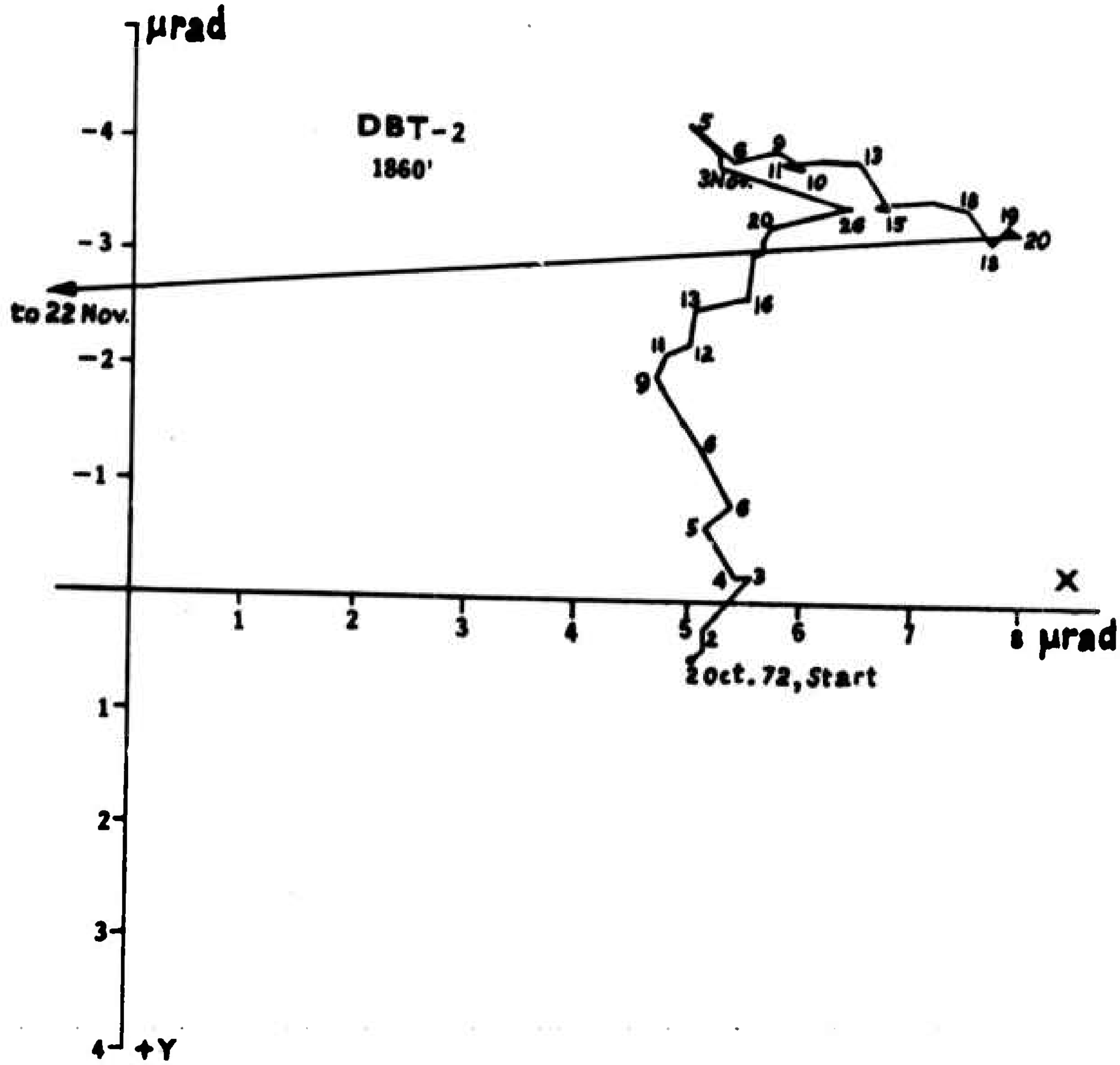

FIGURE 18

X-Y Plot of the Tilt Vector from DBT-2 in the Deep Borehole

(October 2 - November 20, 1972)

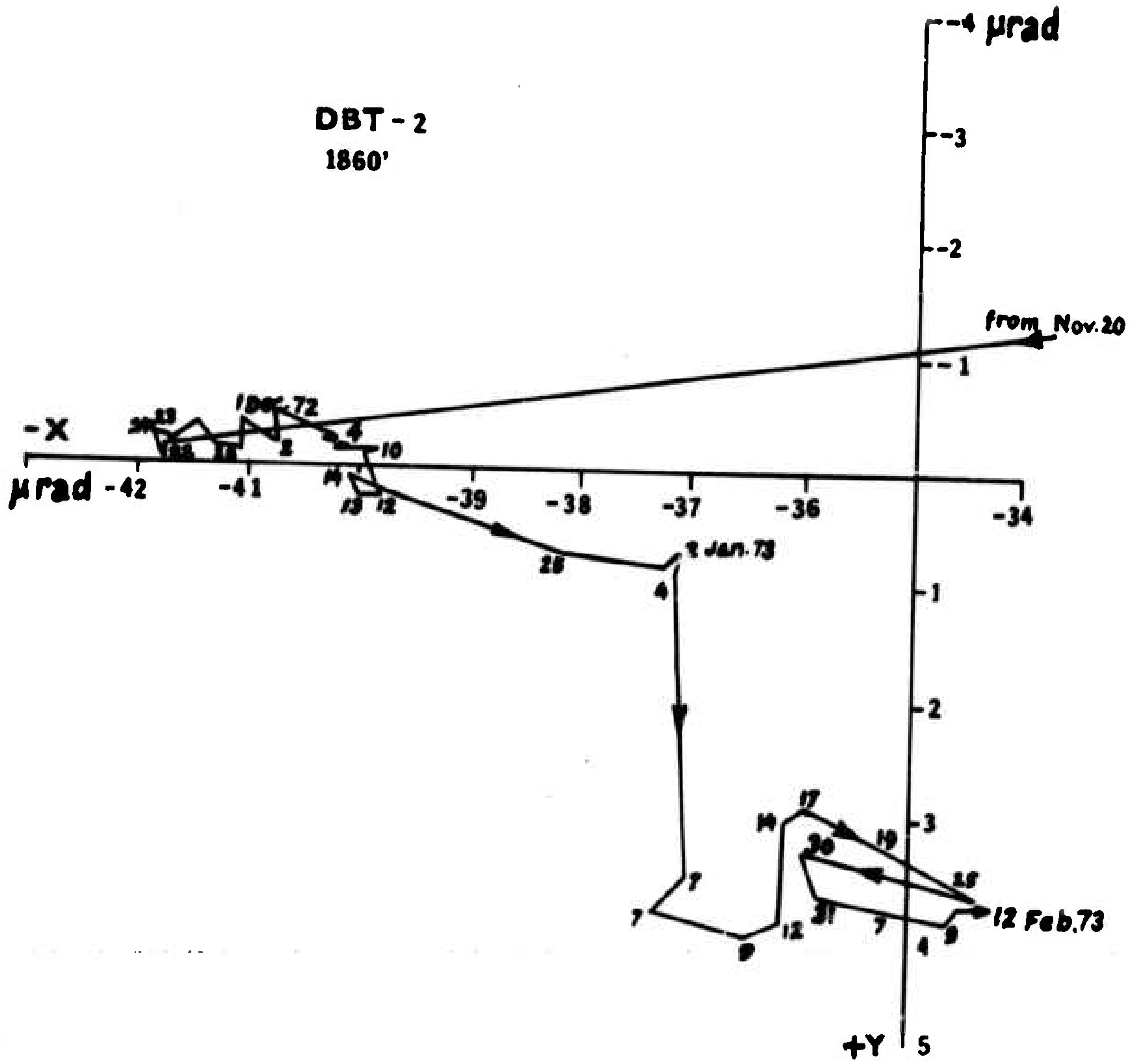

FIGURE 19

X-Y Plot of the Tilt Vector from DBT-2 in the Deep Borehole

(November 22, 1972 - February 12, 1973)

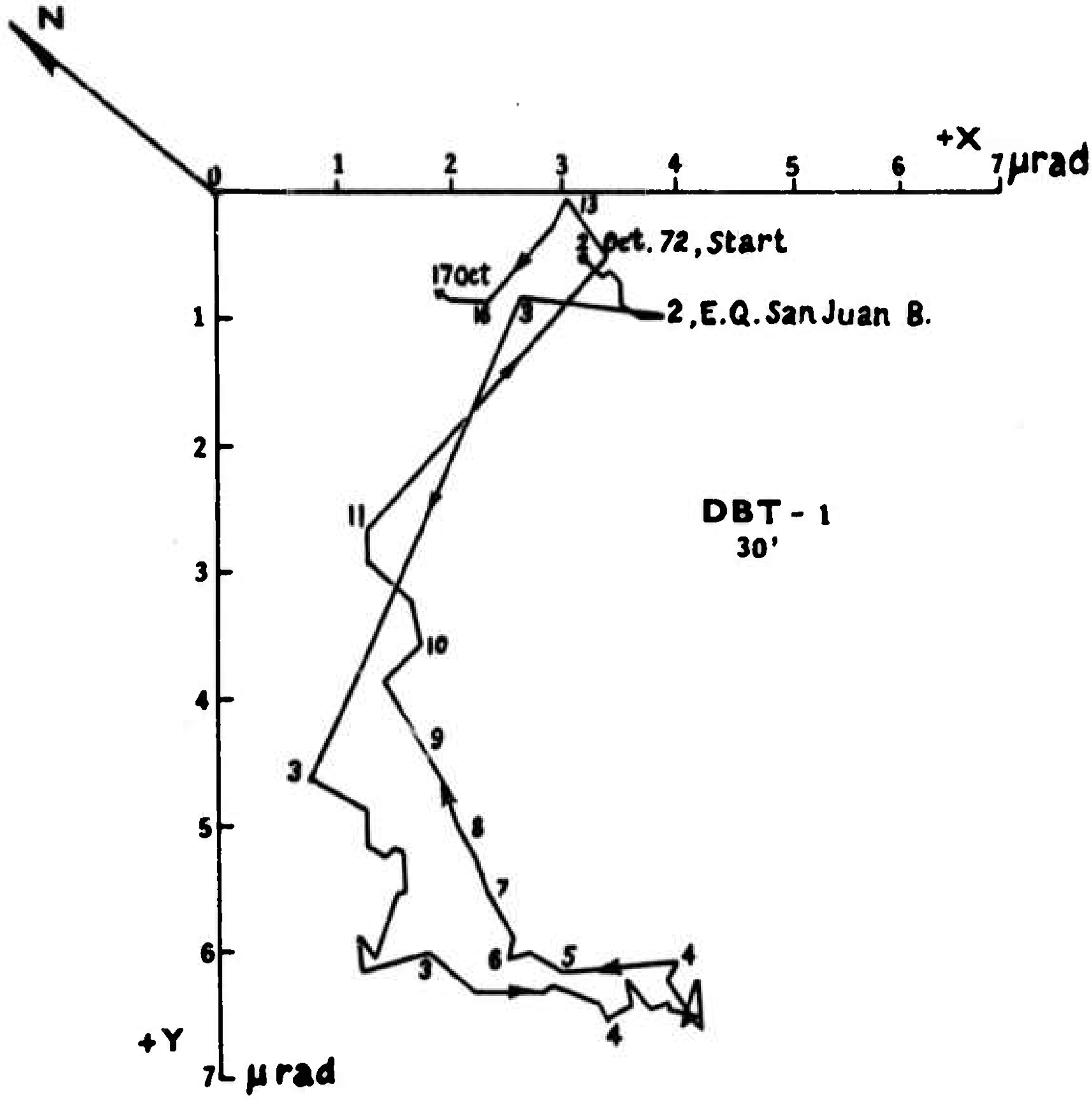

FIGURE 20

X-Y Plot of the Tilt Vector from DBT-1 in the Shallow Borehole